Long-term measurement of frost-heave deformation in geotextile-reinforced soil walls

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ABSTRACT: Some reports have addressed the deformation of geotextile-reinforced soil walls in cold regions. Such deformation is caused by frost heaving of the backfill soil. To control such deformation, the Hokkaido Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism, Japan specifies techniques for constructing reinforced soil walls. The authors have been examining frost-heave countermeasures for geotextile-reinforced soil walls in cold areas and have conducted 9-year continuous measurements of deformation at full-scale embankments constructed during winter. The 9 years of observations have revealed that frost-heave deformation persists after the snowmelt season and becomes cumulative in years after the first year of frost heaving. It was also found that frost-heave deformation can be controlled to some extent by replacing the soil or installing insulation. Based on experimental constructions that involved replacing the soil or installing insulation, replacement using gravel, which is generally used by the Hokkaido Regional Development Bureau, was found to be the most effective way of controlling frost heaving.

Keywords: long-term measurement, frost-heave, geotextile-reinforced soil wall, strain, displacement

1 INTRODUCTION

In constructions such as those for road embankments, soil walls with geotextile reinforcement (hereinafter, geotextile-reinforced soil walls) have been increasing. However, several cases of frost-heave deformation in geotextile-reinforced soil walls have been reported in cold regions. A deformed soil wall is shown in Photo 1. From the photo, it is understood that part of the wall has collapsed from frost heaving and bulging of the embankment soil.

Towards developing measures against such wall failure, the authors conducted experiments on the freezing and frost heaving of reinforced soil walls by constructing full-scale soil walls and measuring the temperature inside the embankment, the strain of the reinforcing material and the deformation of the wall surface for 9 years. This paper summarizes the results.

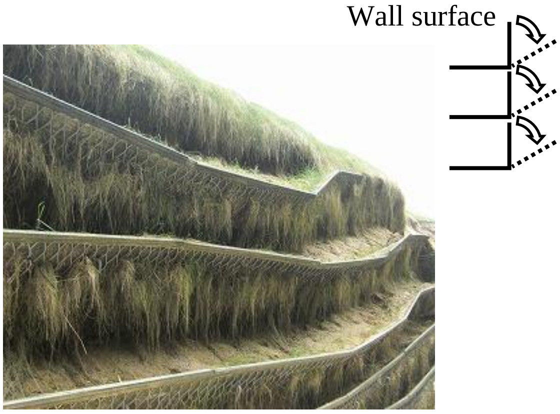


Photo 1. A deformed geotextile-reinforced soil wall.

2 FROST-HEAVE DEFORMATION OF GEOTEXTILE-REINFORCED SOIL WALLS AND THE MECHANISM OF DEFORMATION

In a geotextile-reinforced soil wall constructed using frost-susceptible embankment materials, frost heaving occurs when water is supplied from the back of the wall and the wall surface is exposed to low temperatures. The mechanism of wall deformation from frost heaving is shown in Figure 1. When the soil in an embankment freezes during the cold season, the moisture in the ground that is not frozen moves toward the wall surface. The water from the unfrozen ground freezes near the freezing front in the embankment, layers of ice lenses form with their longitudinal axes parallel to the wall surface, and the embankment expands, that is, frost heave occurs. Because of the expansion of the soil inside the wall, the surface of the reinforced soil wall is pushed outward and deforms. The deformed wall surface does not recover its original shape even after the frozen soil thaws after the air temperature rises. It was found that frost heaving repeatedly occurs for several years after construction and that the deformation accumulates during those years.

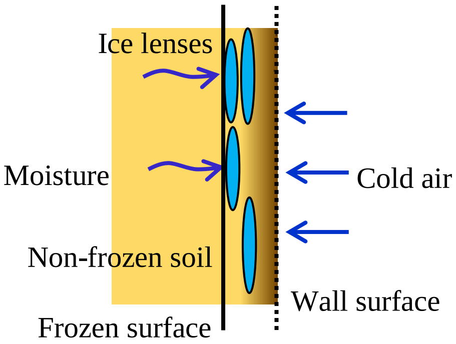


Figure 1. Frost heave deformation of a geotextile-reinforced soil wall, and the mechanism of deformation.

Frost heaving occurs when the three factors for frost heaving are present: poor soil, low temperature, and water. In controlling deformation from frost heaving, it is effective to eliminate at least one of these three factors. To control deformation from frost heaving in reinforced soil walls, the Hokkaido Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism specifies that the material at the location of frost heave should be replaced with a layer of a non-frost heaving material (i.e., a frost blanket) over the front surface of the reinforced soil wall. The advantages of this technique include the possibility of draining the water inside the reinforced soil wall through the non-frost heaving material, and controlling deformation from frost heaving by replacing the frost-susceptible material with non-frost-heaving material.

3 EXPERIMENT METHOD

Full-scale embankments had been constructed to clarify the mechanism frost-heave deformation in geotextile-reinforced soil walls. Measurements done for these full-scale embankments were continued.

3.1 *Specifications of the full-scale reinforced soil wall*

Full-scale embankments were constructed in a suburb of Tomakomai City, Hokkaido, northern Japan. The full-scale embankments were constructed from the materials shown in Table 1. These embankments were measured for deformation. The embankment materials are volcanic ash, whose maximum dry density is hard to clearly determine. The cone index determined in the trafficability test was 3000kN/m^2 or greater. The workability of this material was good, and such volcanic ash is relatively easy to compact. The material has the potential to undergo frost heaving because the material has moderate frost-heave susceptibility.

Four types of reinforced soil walls were constructed: a wall without any anti-frost heave measures (CASE 1), a wall with air insulation from the installation of a loofah-like structure (CASE 2), a wall with air insulation from the installation of a palm mat (CASE 3), and a wall in which replacement material was used (CASE 4). In the case of soil replacement, the gravel shown in Table 1 was used as the non-frost-heaving material. The range of replacement was 80cm, as specified by the Hokkaido Regional Development Bureau for the 20-year-probability maximum theoretical frost penetration depth for the Tomakomai Area. In determining the replacement depth for pavement, the maximum theoretical frost penetration depth is multiplied by the replacement ratio. However, the replacement depth for reinforced soil walls is determined as the theoretical maximum depth, because frost heaving in a reinforced soil wall progresses perpendicular to the direction of gravitational force.

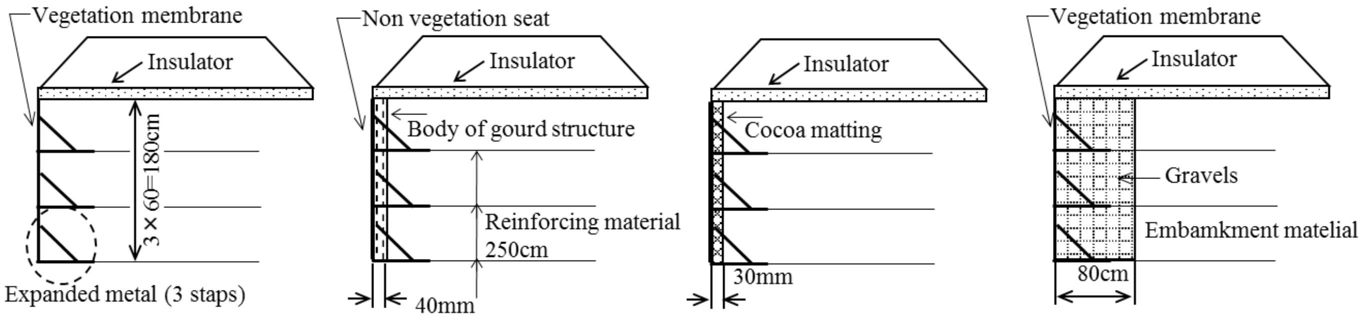
Table 1. Basic physical property values of fill material.

Physical property		Volcanic ash	Gravel
Soil particle density ρs (g/cm^3)		2.470	2.739
Natural water content wn (%)		46.98	11.01
Grain size	2 mm or larger (%)	22.8	38.8
	75 μm to 2 mm (%)	51.4	52.3
	Less than 75 μm(%)	25.8	8.9
Consistency limit		N.P.	N.P.
Classification symbol of soil material		SVG	SG-Gs
Frost heaving	Velocity of frost heaving (mm/hr)	0.27	-
	Percentage of frost heave (%)	18.1	-
	Degree of frost heaving	Medium level	-
Permeability coefficient k (cm/sec)		2.34×10^{-5}	$\times10^{-3}$
Maximum dry density ρ_{dmax} (g/cm^3)		Not determined	2.050
Optimum water content w_{opt} (%)		-	10.5
Cone index qc (kN/m^2)		3000 or larger	3000 or larger

The reinforced soil wall was constructed in a soil chamber of 5m in height by 5m in length by 2m in depth. Each reinforced soil wall was constructed on a 30cm-thick layer of drainage gravel. The reinforced soil wall was constructed as a three-layer structure in which each layer was 2.4m wide by 60cm high by 3.0m deep. Two walls were constructed in each soil chamber. The space between the two walls was insulated with a 10cm-thick foam polystyrene board to prevent the two walls from thermally influencing each other.

Table 2. Outline of test cases.

CASE	Control Measure	Year of construction	Specific measure	Vegetation
1	None	2008	Standard	Existing
2	Insulation	2009	Gourd-shaped body 40 mm + unwoven cloth 1 mm	None
3	Insulation	2008	Cocoa matting with a thickness of 30 mm	None
4	Replacement	2008	Replacement with gravels (0.8 m from wall surface)	Existing



a. CASE1 b. CASE2 c. CASE3 d. CASE4

Figure 2. Details of the experiment cases.

The specifications for each experiment case are shown in Table 2 and Figure 2. These four experimental walls were constructed in December 2008. The wall surface was expanded metal. For CASE 2, a reinforced soil wall without any wall surface covering material had been constructed in 2008; however, the wall surface was found to have collapsed slightly. When the wall surface of the CASE 2 wall was repaired, an insulating material with a loofah-like structure, a structure that is regarded as excelling in resistance to heat and cold, was installed. For reinforced soil walls constructed in the real world, frost heaving occurs because water is supplied from behind the embankment. However, it is structurally impossible to supply water to an embankment that is constructed in a soil chamber. To reproduce the real-world frost heaving environment as closely as possible, the experimental reinforced soil walls were submerged in water for about 2 weeks before winter. Immediately before the soil started to freeze, water was drained to the height of about 10cm above the drainage gravel layer. These two conditions were regarded as reproducing the water supply to the reinforced soil walls. The initial setting of the experimental reinforced soil wall in the soil chamber allowed the front and top surfaces of the wall to cool. To correct the structural setting to that which would allow cooling to occur only on the front surface of the wall, the top surface of the wall was covered with a 10cm-thick EPS insulating material, and the insulating material was covered with a 50cm-thick layer of volcanic ash that was the same material as used for the embankment. The front surface of each reinforced soil walls faced north, and the slope of the walls was plumb.

3.2 *Measurement items*

The measurement items and methods are shown in Table 3, and the locations of measurement are shown in Figure 3. The strain at the top and bottom surfaces of the reinforcing material for the middle layer and the temperatures near these areas were measured. The horizontal displacement of the wall surface material was measured as the distance from a leveling string that was set vertically along the surface of the wall of the soil chamber.

Table 3. Measurement items and method.

Measurement item	Points of measurement	Measurement instrument	Measuring method	Interval of measurement
Temperature	At the boundary between the first and second stages from the bottom and in the air 10 cm	Thermoelectric thermometer	Automatic	One hour
Earth temperature	At the boundary between the first and second stages from the bottom, near the top surface of thermometer reinforcing material at the second stage and at points 10, 30, 50, 70, 90 and 140 cm from the wall surface.	Thermoelectric thermometer	Automatic	One hour
Strain of geotextile	At the boundary between the first and second stages from the	Strain gauge	Automatic	One hour
Horizontal displacement of wall surface material	Top and bottom of the first and second stages from the top of geotextile-reinforced earth wall.	Scale	Measurement by person	One week – 6th month

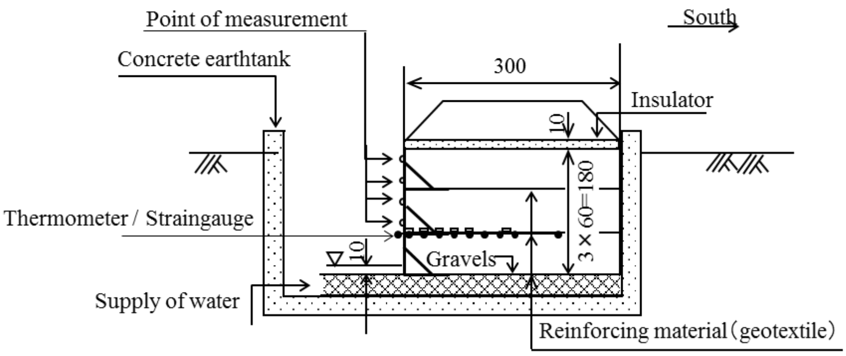


Figure 3. Locations of measurement instructions installed in the model wall.

4 MEASUREMENT RESULTS

4.1 *Frost penetration depths of the embankments with reinforced soil walls*

Figure 4 shows the frost penetration depth of each reinforced soil wall. The mean temperature was determined from the ambient temperatures measured 10cm from the surface of the reinforced soil wall. The frost penetration depth was determined by calculating the depth where the temperature would be 0°C. The cumulative daily mean temperatures is the highest for CASE 1, followed by CASE 2, CASE 3 and CASE 4. The wall material in CASE 1 had sand and soil immediately behind the wall surface material. The wall surface material in CASE 2 had a 4cm-thick loofah-like structure behind it, that in CASE 3 had a 3cm-thick palm mat behind it, and that in CASE 4 had an 80cm-thick gravel layer behind it. The ambient temperature differed depending on the material used behind the wall surface material. The frost penetration depths for CASE 1, CASE 2 and CASE 3 were nearly equal, but that for CASE 4 was greater than those for the other three. The frost penetration depth was greater fro CASE 4 than for the other cases because the thermal conductivity of gravel is higher than that of soil.

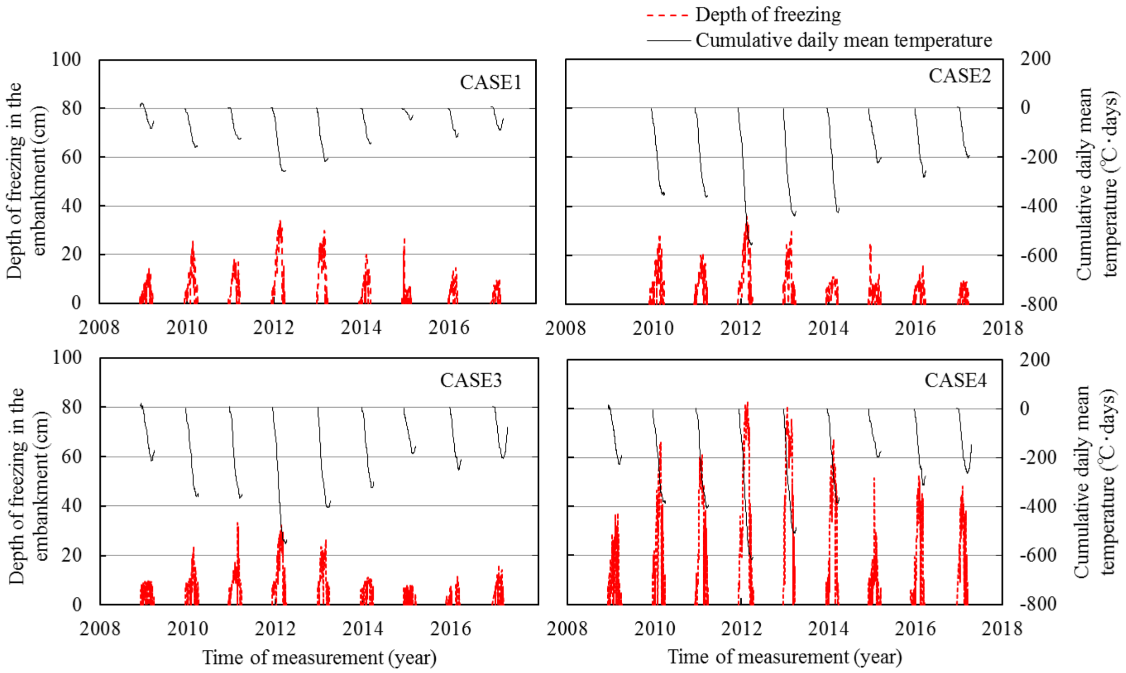


Figure 4. Frost penetration depth and cumulative daily mean temperature of each case.

The freezing index and the maximum frost penetration depth of the soil in the reinforced soil wall are shown in Figure 5. When the freezing index is the same for all four cases, the frost penetration depth for the soil in the four embankments is the smallest for CASE 4, followed by CASE 3, CASE 2 and CASE 1. It was not always possible to estimate the frost penetration depth from the freezing index, because the freezing indexes differed depending on the material behind the wall surface material in this study. In CASE 4. The soil in the embankment remained nearly unfrozen.

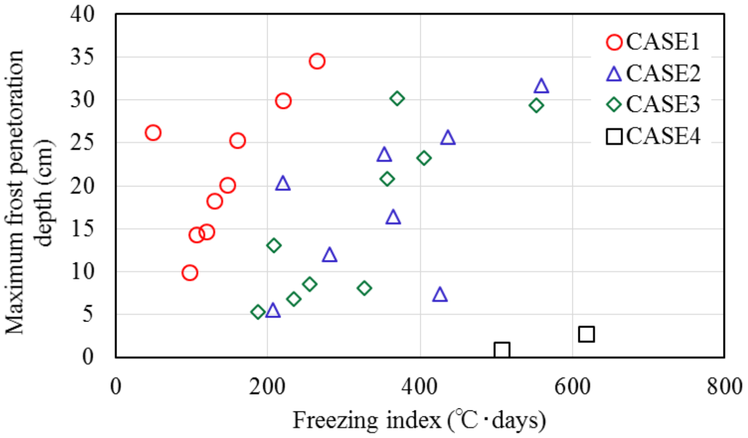


Figure 5. The freezing index vs. the maximum frost penetration depth for the soil portion of the embankment.

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4.2 *Strain of the reinforcing material*

The strain of the reinforcing material for each soil wall is shown in Figure 6. The strain is the average of values measured by strain gauges attached to the top and bottom surfaces of the reinforcing material. For the measurement case in which one of the strain gauges malfunctioned during the long period of measurement, only the value from the strain gauge that functioned properly is shown in the figure (the broken lines). The maximum frost penetration depth is also shown in this figure. In CASE 1 and CASE 3, the strains in the tension direction are great, except for the strain measured at 140 cm from the wall surface. The strain became small in the melting season, but it did not become zero. The strain became small shortly before the melting season started; however, residual strain remained until the next freezing season started. The maximum frost penetration depth measured from 2010 to 2013 was about 30cm. During this period, the changes in strain were considerably great at 30cm inward from the wall surface. The maximum frost penetration depth measured from 2014 to 2017 was about 10 to 20cm. During this period, the changes in strain were great at 10cm inward from the wall surface. In 2014 and after, the residual strain was largely absent. Although strain from frost heaving occurred in the reinforced soil wall, the strain became about the same value as that before freezing in the melting season. In CASE 2, which lacked a large portion of data for the soil near the maximum depth of frost penetration, the relationship between the maximum depth of frost penetration and the location of strain occurrence was not determined. However, the tendencies of the strain, which remained in the melting season until 2013 and disappeared in and after 2014, were similar between CASE 2 and the other cases. In CASE 4, no tendency for the strain to increase during the freezing season was observed at 10cm, 30cm, 50cm, and 140cm inward from the wall surface. In CASE 4, the maximum frost penetration depth was between 60cm and 80cm. The changes in strain for locations at 70cm and 90cm inward from the wall surface were relatively great.

The tendency as a whole was for the strain of the reinforcing material near the maximum frost penetration depth to be greater than at any other location. In and after 2014, which was the 6th year after the construction of the soil walls, residual strain was not found because the strain of reinforcing material that occurred during winter disappeared in summer. No residual strain was found from the 6th year onward. Further accumulation of data is necessary to clarify the relationship between the time (years) after construction and the residual strain, because, as shown in Figure 4, the winters in and after 2014 tended to have temperatures higher than those before that period, which might have influenced the relationship between the time after construction and the residual strain. As the strains in all four cases were less than 5%, which is the permissible value for strain, the four methods are expected to be sufficiently safe for the construction of a reinforced soil wall.

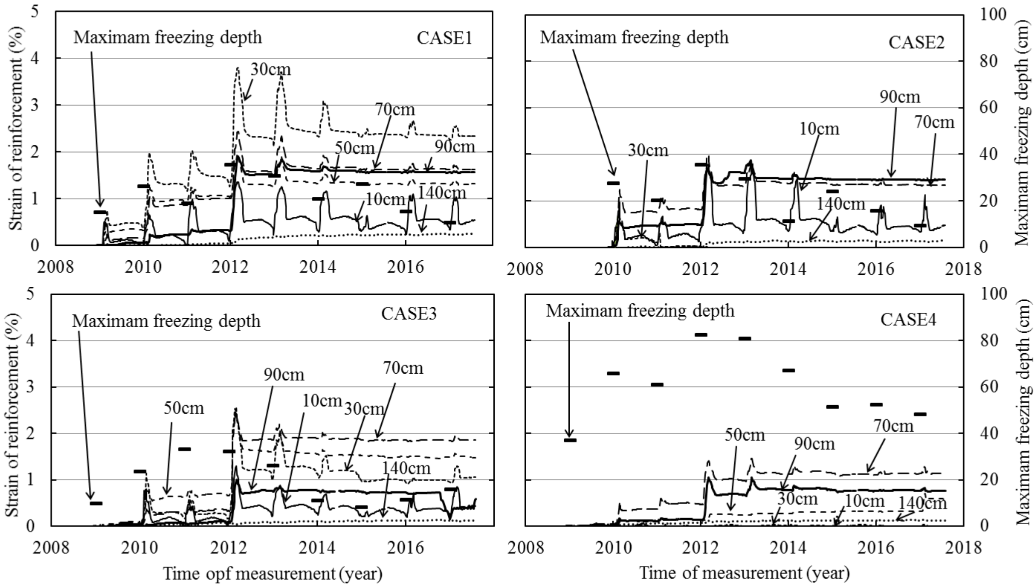

Figure 6. Strain in the reinforcing material.

4.3 *Horizontal displacement of the surface of a reinforced soil wall*

The horizontal displacement of the surface of the reinforced soil wall is shown in Figure 7. The displacement of the wall surface was measured at three points along the top and bottom lines of the wall surface for the top and 2nd layers. The values for each three points were averaged. The displacement was found to be the greatest at the top of the top layer and the 2nd greatest at the top of the 2nd layer in all four soil walls. The deformation at the bottom of the top and 2nd layers of the soil wall were nearly equal, except for CASE 3. The displacement in all four soil walls varied in degree. The wall surface material expanded outward immediately after the freezing season started and slightly recovered to the original position after the embankment material completely melted; however, the recoveries were incomplete. In the following winter, the wall surface displaced outward again during the freezing period. The above-described process continued for the 9 years of displacement measurements, and the residual outward displacement accumulated. The displacement was the smallest in CASE 4, in which replacement with gravel had been done. The degrees of displacement for CASE 1 and CASE3 were nearly equal. CASE 2 had less displacement than CASE 1 and CASE 3, presumably because the measurement period for CASE 2 was one year shorter than for the other two cases.

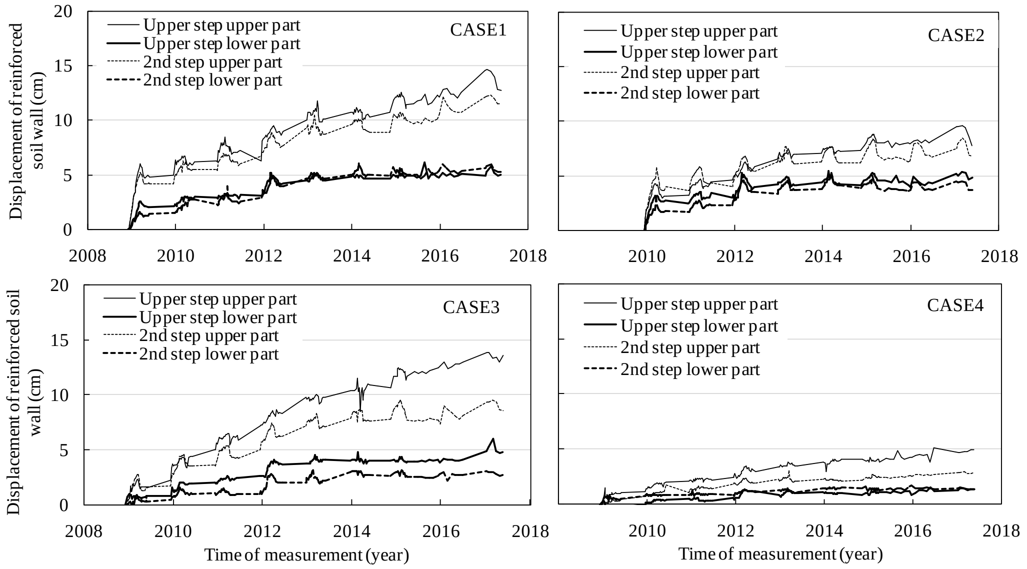

Figure 7. Horizontal displacement of the surface of reinforced soil wall.

Next, the displacement of the wall surface of the reinforced soil wall was investigated in winter and summer. Figure 8 shows the displacement of the wall surface at the top of the top layer, where the changes in displacement were the greatest. The figure shows the greatest displacement of the wall surface in winter and in summer for each year after construction completion. The greatest displacement occurred in winter of the first year. From the 2nd year to the 6th year, when the freezing index was high, the displacement in winter tended to be great. The displacement was greater in winter than in summer from the construction completion to the 6th year. The winter displacement was small in the 7th and 8th years. The freezing index was small for each of these two years; therefore, it is not possible to determine whether the small displacement was from the termination of displacement or from the reduced influence of the cold. Follow-up investigations will be necessary. The wall surfaces of the reinforced soil walls continued their outward displacement even long after construction completion. This agreed with the results of a previous study.

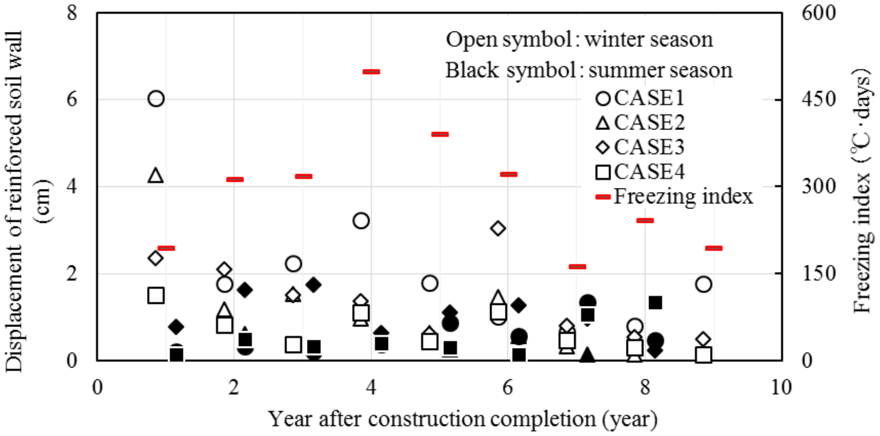

Figure 8. Displacement of the wall surface of the reinforced soil wall in winter and in summer.

5 SUMMARY

To investigate the frost-heave deformation of geotextile-reinforced soil walls, full-scale models were constructed. The investigation revealed the following.

[1] Displacement of the wall surface and strain in the reinforcing material from frost heaving occur in some geotextile-reinforced soil walls. The greatest displacement of the reinforcing material occurred near the maximum frost penetration depth. The displacements and strains tended to accumulate year after year, even though the embankment soil melted in the summer.

[2] As a measure against frost heaving in geotextile-reinforced soil walls, a method in which the frost-susceptible material is replaced with non-frost susceptible material was found to be more effective than methods involving the installation of insulation. It was also found that, in methods involving the installation of insulation, it is necessary to understand the physical properties of the insulation materials, because this investigation clarified that the insulation materials were of greatly differing effectiveness.

REFERENCES

Atsuko, S., Satoshi, N., & Naoki, T., 2012. Elucidation of and Measures against the Factors Involved in the Deformation of Geotextile-reinforced Soil Walls Due to Frost Heaving, the 55th Hokkaido Development Technology Conference, Hokkaido Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism

Atsuko, S., Takahiro Y., Teruyuki, S., Naoki, T., & Kouichi, Y., 2014. Frost Protection for Geotextile-reinforced Soil Walls in Service, Soil-Structure, Interaction. Underground Structures and Retaining Walls, ISSMGE Technical Committee 207. 6.

Geotechnical library 23、The Japanese Geotechnical Society, 1994. Soil Freezing - Its Mechanism and Actual Conditions

Hokkaido Regional Development Bureau, Road Design Guidelines
https://www.hkd.mlit.go.jp/ky/kn/dou_ken/ud49g70000001ly2-att/splaat0000003v49.pdf

Japan Road Association, 2009. Road Earthwork Guideline p.287

Japan Road Association, 2009. Road Earthwork Guideline p389.

Shunzo, K., Satoru S., & Nobuyuki, T., 2011. Case study on mechanical behavior of a largely-deformed reinforced earth wall、Japanese Geotechnical Journal. Vol.6, No.1, 15-25,.

The Japanese Geotechnical Society, 1994. Soil Freezing - Its Mechanism and Actual Conditions

The Japanese Geotechnical Society, 2009. Frost Heave Test Methods for Determining the Amount of Frost Heave; Frost Heave Test Methods for Determining Susceptibility to Frost Heaving; New Standards Established by The Japanese Geotechnical Society and the Guide to the New Standards, p. 247

ttps://www.hkd.mlit.go.jp/ky/kn/dou_ken/ud49g70000001riu-att/splaat0000003vne.pdf#search=%27%E5%8C%97%E6%B5%B7%E9%81%93%E9%96%8B%E7%99%BA%E5%B1%80+%E9%81%93%E8%B7%AF+%E5%87%8D%E7%B5%90+%E7%BD%AE%E6%8F%9B%E5%8E%9A%27

Yoshida, K., Shinmura J., & Suzuki T., 2009, Report on the Deformation of Geotextile-reinforced Soil Wall Surface in Cold Regions, the 44th Workshop of The Japanese Geotechnical Society, pp. 809-810