In-situ tests of countermeasure technique for the frost heave on cut slopes using geocell and thermal insulation material

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ABSTRACT: Hachinohe area, located in northeastern Japan, has a climate of low temperature and less rainfall during the winter period. In this area, volcanic cohesive soil is widely and thick deposited, called Takadate loam. This soil is unique to the area and susceptible to the frost heaving action. In many cases, no active construction measures against frost heaves have been taken on the cut slope, and in recent years these problems often occur and have become a regional problem. In this study, we examined seven countermeasure methods, which were carried out in-situ tests. And from the test records the thermal conductivity of the soil was calculated, and the thickness of the heat insulating layer was induced by an analysis, and the integrity of in-situ tests results was verified. As a result, we confirmed the method of calculating the insulation thickness and the possibility of a measure method that does not use a heat-insulating material.

Keywords: cut slope, geocell, frost heaves

1 INTRODUCTION

Hachinohe area is located on the Pacific side of northeastern Japan. The temperature in the winter period is low and there is a little snowfall. The amount of precipitation is about 40 mm/month. The average annual temperature is 10.2 degrees, and the average monthly temperature in January and February is lower than 0 degree Celsius. In addition Celsius, it is not more than around 2-3 degree Celsius even if the temperature rises. In the vicinity of Hachinohe, there is soil peculiar to the area called Takadate loam, which is deposited in a wide area with volcanic cohesive soil. Takadate loam has high moisture content and soil is susceptible to frost heave. However no positive construction measures against frost heave have been taken on the cut slope of Hachinohe area. In many cases, this cut slope is often exposed and the repetitive freeze-thaw cycle ultimately causes strength deterioration, and this is a serious problem in the Hachinohe area.

The frost heave of the soil ground is caused by the soil properties, water content of soil and underground temperature. In cut slopes, it is very difficult to control the soil properties and water content. Therefore, it is considered necessary to control the underground temperature for preventing cut slopes from being damages by frost heaves. In this study, we carried out in-situ tests for the purpose of developing frost heaving measure construction methods.

2 IN-SITU TEST

2.1 *Experiment cases*

The cases of the in-situ tests are shown in Table 1, and a plan view of the cutting surface and a representative sectional view of the cases are shown in Figure 1. The inclination of slope is 1: 1.5 westward. The slope was further cut with a thickness of about 30 cm, under the condition of the mountain surface exposed, and in 7 cases of the countermeasures geocells were laid. Also, for the purpose of comparison, Case 8 was prepared with the ground exposed.

Table 1. The cases of In-situ test

Case No.	1	2	3	4	5	6	7	8
Geocell thickness (mm)	100						150	No measures
Thermal insulation thickness (mm)	100		50		None			
Filling material	Natural sand	Crushed stone		Natural sand	Crushed stone	Artificial light-weight granular material		

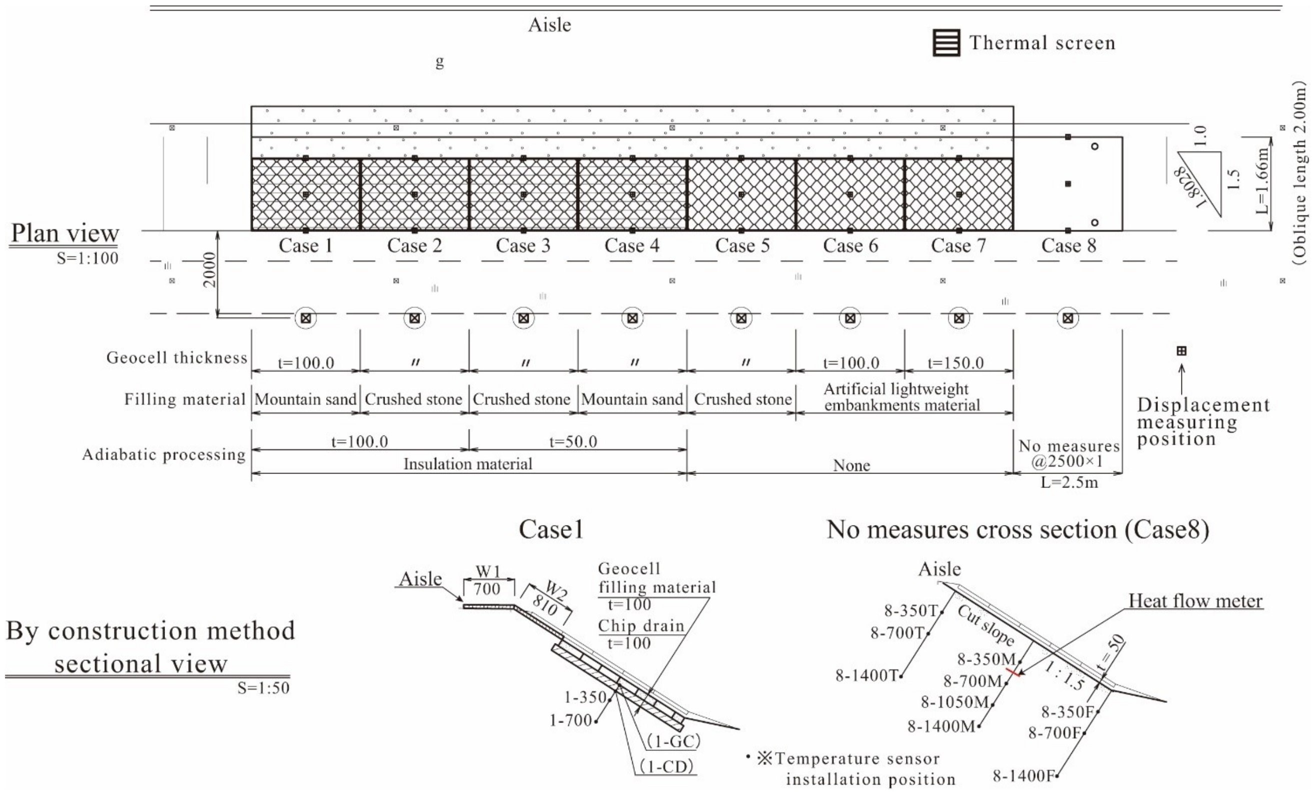

Figure 1. On-site plan view

2.2 *Measurement items*

The measurement items in the in-situs test are the frost heave amount (the displacement of the ground surface), the underground temperature, the temperature just under the countermeasure construction method, the outside temperature and all of the solar radiation amount in the sky. Temperature sensors were buried at the center of the slope of each countermeasure method and they were set at the depth of 350 mm and 700mm from the surface of the cut slope. In Case 8, the sensors were buried not only at the center of the slope but also at the top and the toe of the slope, and the additional sensor at the depth of 1400mm to measure the underground temperature. The sampling of each data measured was taken by the program of the sensor for 30minutes. The temperatures were measured in a thermal screen near the slope. The displacement measurement was carried out by seven survey markers which were installed in the direction of the slope using for surveying equipment (TS). Also, these markers were measured from survey piles buried near the slope. Coordinates were decided from a result of the surveying, and the displacement of the slope surface was calculated by their difference. The displacement of the slope surface was measured on

December 19, 2014 (initial coordinates), February 23, 2015 (maximum frost heave amount) and April 23, 2015 (after frost heave).

2.3 *Materials used for filling*

The materials used for filling in the geocell are mountain sand, crushed stone C-40, and artificial lightweight granular materials. Figure 2 shows the local soil and the filling materials used. In addition, an expanded polystyrene lightweight drainage material was used as a heat insulating material. The maximum grain size, hydraulic conductivity and unit weight of the materials used are shown in Table 2, the other fundamental properties are shown in Table 3, and the grain size accumulation curves of mountain sand and local soil are shown in Figure 3. From the grain size accumulation curves, the passing percentage of 0.1mm, which is said to cause frost heaves easily, is 75% contained. Therefore, it can be said that frost heaves occurs easily in this local sand (Kuroda 2006).

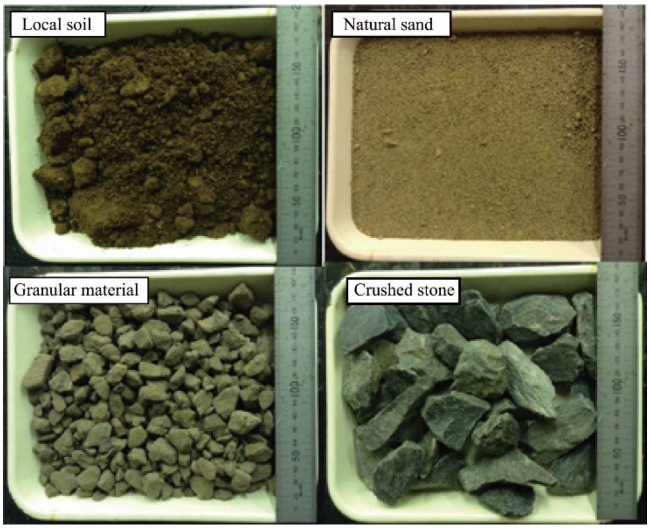

Figure 2. Materials used for filling

Table 2. Fundamental properties

Sample name	Local soil	Natural sand	Crushed stone	Artificial lightweight granular material	Thermal insulation
Maximum grain size (mm)	4.75	4.75	75	19	-
Hydraulic conductivity (cm/s)	-	6.77×10^{-3}	6.77×10^{-2}	4.10×10	2.0×10^{-1}
Unit weight (tf/m^3)	1.223	1.513	1.6	1.1	-

Table 3. The other fundamental properties

Sample name	Local soil		Natural sand
Soil particle density (g/cm^3)	2.315		2.312
Uniformity coefficient	60		2.93
Coefficient of curvature	3.75		1.27
D50	0.034		0.38
Fine fraction content	70.99		1.94
Maximum soil particle density (g/cm^3)	-		1.532
Minimum soil particle density (g/cm^3)	-		1.207
Optimum moisture content	-		16.71
Maximum dry density (g/cm^3)	-		1.705

Natural water content (%)	86.36		-
Liquid limit (%)	124.5		
Plastic limit (%)	94.59		
plasticity index	29.91		
Unconfined compression strength	98.25		
Strain at failure (%)	3.47		
Deformation modulus (MN/m^2)	3.15		
Void ratio	3.07		
Wet density (g/cm^3)	1.225		
Dry density (g/cm^3)	0.651		

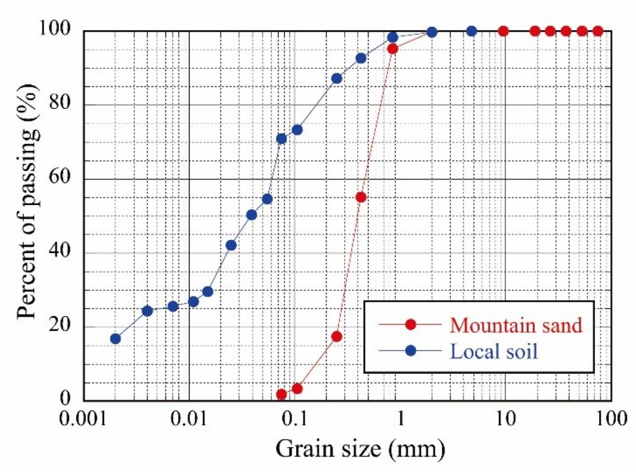

Figure 3. Grain size accumulation curve

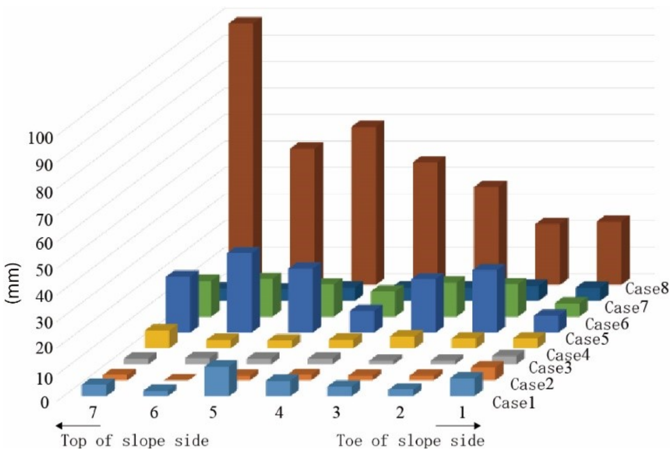

Figure 4. Ground surface displacement

2.4 *Results of the in-situ test*

Figure 4 shows the displacement of the slope surface in each countermeasure from December 25, 2014 (initial coordinates) to February 23, 2015 (maximum frost heave amount). This figure shows the displacement amount at each survey point measured for each countermeasure. The displacement in this figure is shown only in the vertical direction.

First, in Cases 1 to 4, the thermal insulating material was laid under the geocell, and it is clear that the slope surface displacement is smaller in these cases than in the cases without the thermal insulating material. From this fact, it is considered that the thermal insulating material effectively acts to suppress the frost heave amount. When Case1 is compared with Case4 in this figure, there is little difference in displacement. Also, no difference is seen between Case 2 and Case 3. From this, it can be said that there is no difference in frost heave amount depending on the thickness of the heat insulating material. It was judged that breaks occurred due to the unevenness of the cutting surface in thinning the geocell. From the results, it is considered that if the thickness of the thermal insulating material is 50 mm, as long as it is similar to this experimental condition, it is possible to prevent frost heave sufficiently. On the other hand, the influence due to the difference in the filling materials filled into the geocell is somewhat observed. Compared with the case of filling crushed stone, the amount of frost heaves is larger when mountain sand is used as the filled material. However, this difference is thought to be the frost heave amount of the geocell layer itself, and it is considered that it is not the frost heave amount of the ground at a position deeper than the thermal insulating layer.

Next, Cases 5 to 8 are cases without the thermal insulating materials. In Case 7, it is obvious that the frozen volume is small when the lightweight embankment material having a thickness of 150 mm is used. The difference is clear even compared with Case 6, which differs only in thickness, and it can be said that a lightweight embankment material layer that is a porous material is effective as a thermal insulating layer. From the above, under the conditions of the in-situ test in this research, it seems that the threshold of whether or not there are frost heaves will be about 150mm thickness of the light weight filler material.

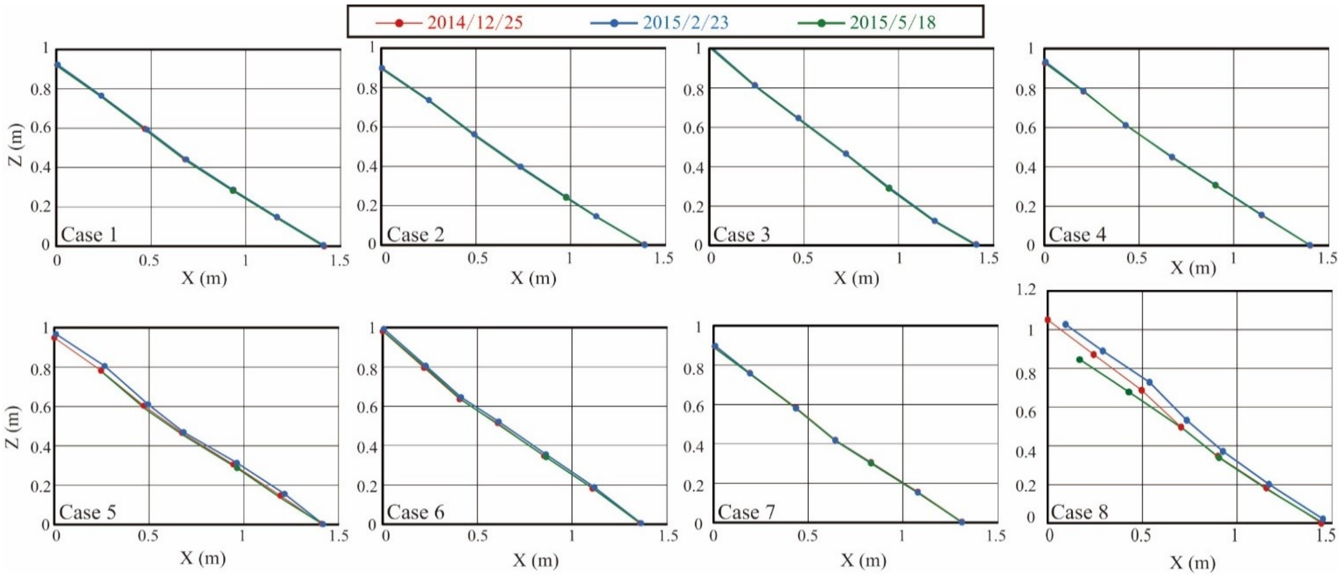

Figure 5. Displacement of ground surface by frost heave

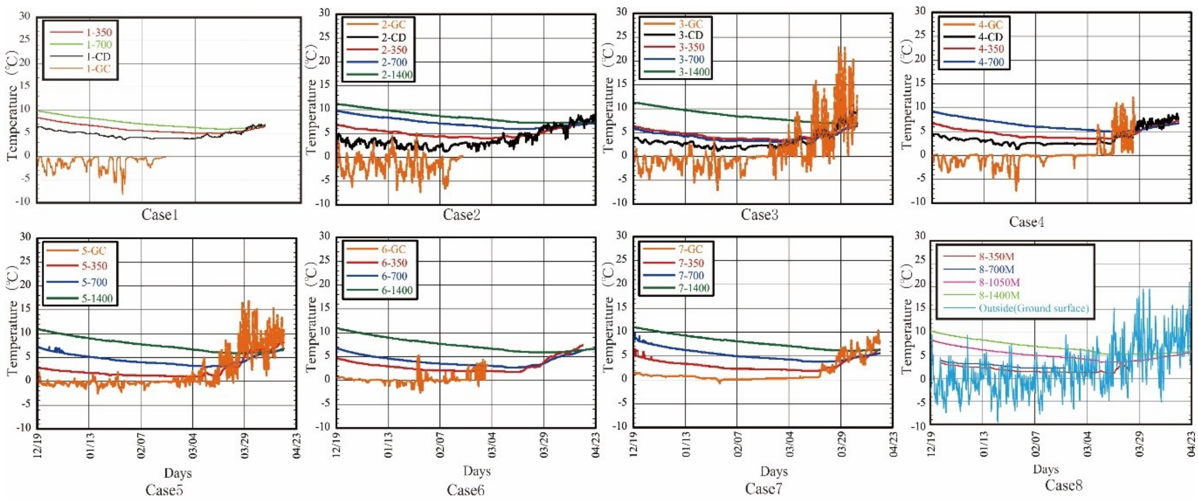

Figure 6. Underground temperature of each experiment

Next, not only the vertical direction but also the displacement in the countermeasure cross section will be examined. Figure 5 shows the amount of displacement in cut slope cross section of each countermeasure. The figure shows not only the vertical direction but also the displacement amount in the horizontal direction. In Case 8, it can be seen that the ground surface position after frost heaving-thawing is displaced downward and frontward from the position at the initial stage of construction in the upper portion of the slope, where displacement due to the frost heave effect is large. At first, the surface of the slope is displaced in the normal direction of the slope due to the frost heave effect, then it is seen that the surface of the slope is displaced vertically downward from the gravity.

Figure 6 shows the underground temperature results of each point measured for each case by the buried sensor. Regarding the legends in the figure, ◯-GC indicates the temperature just under the geocell, and ◯ - CD indicates the temperature just below the heat insulating material. From this figure, when Case 8 is compared with the other cases, the ground surface temperature is higher than counterpart of Case 8, where the fround was exposed with no measures. The same can be said about other than the ground surface. In addition, the ground surface cases 1 to 4 are high because they are protected by thermal insulation.

However, when counterpart in thickness of the insulating layers, the temperature 50mm is lower by 2 to 3 degree Celsius than with 100 mm. It is also understood that if the insulating layer becomes thinner than 50mm, it will reach the threshold of frost heaves. When the temperatures directly under the geocell are compared, the case using crushed stones shows more rapid and severe temperature change than the case using mountain sand. Since the grain void is large and continuous, it is considered that it is easy to follow the outside air temperature. On the other hand, in the case of mountain sand, the temperature change is smooth, the swing width is small, and it does not drop below the freezing point.

3 THE THICKNESS OF THE THARMAL INSULATING MATERIALS

3.1 *Modeling as the one-dimensional steady thermal conductivity*

We considered about the one-dimensional thermal conductivity problem perpendicular to the slope as shown in Figure.7. T_A is the air temperature, and T_s is the temperature at the position of depth t_S from the ground surface, both of which are shown as being constant. First, the heat release q from the surface of the thermal insulating material into the air can be expressed by the following equation by the heat radiation q_r by radiation and the heat radiation q_c by convection (Kawamura and Hijikata 1995, Odake et al. 1994).

$$q = q_r + q_c \tag{3}$$

The heat dissipation due to radiation from the surface of the thermal insulation material into the air can be written as follows, using the Stefan-Boltzmann constant σ and emissivity ε.

$$q_r = \sigma\varepsilon(T^4{}_1 - T^4{}_A) \tag{4}$$

In addition, the heat radiation q_s by convection can be written as follows.

$$q_c = h(T_1 - T_A) \tag{5}$$

Here, h is the coefficient of heat transfer. When Equation (4) and Equation (5) are substituted into Equation (3), the heat radiation from the surface of the thermal insulating material into the air is given by the following equation.

$$q = \sigma\varepsilon(T^4{}_1\text{-}T^4{}_A) + h(T_1\text{-}T_A) \tag{6}$$

In the steady state, the heat flux q_s in the solid becomes equal to the heat release q from the solid surface (in this case, the surface of the thermal insulating material) into the air, and the following equation completed.

$$q = q_s \tag{7}$$

Therefore, according to Fourier's law concerning heat flow in the ground and in the heat insulating material, the following equation is obtained.

$$\begin{aligned} T_2 &= T_S - \frac{q}{\lambda_s} t_S \\ &= T_1 - \frac{q}{\lambda_I} t \end{aligned} \tag{8}$$

Where λ_s is the thermal conductivity of the ground, λ_I is the thermal conductivity of the insulating mate-

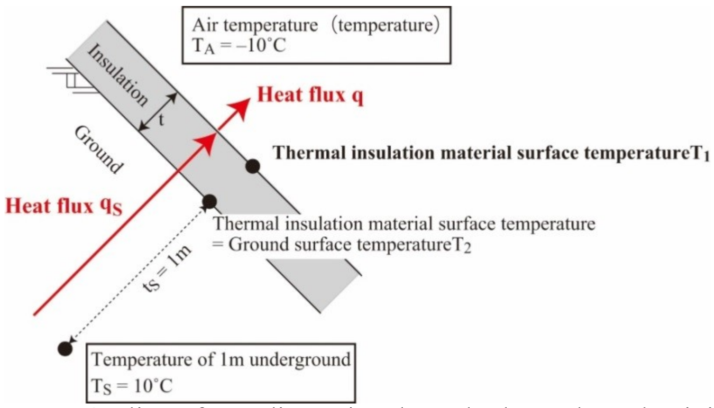

Figure 7. Outline of one-dimensional stesdy thermal conductivity

rial, t_S and t are their thickness respectively.
In this study, q is obtained from equation (6) supposing T1, and T2 that satisfies equation (8) is found. It is known that frost heaves can be completely prevented unless the temperatureT2 of the foundation ground surface under the thermal insulation material falls below 0 degree Celsius. For that reason, T2 will be investigated further by changing the thickness t of the heat insulating material.

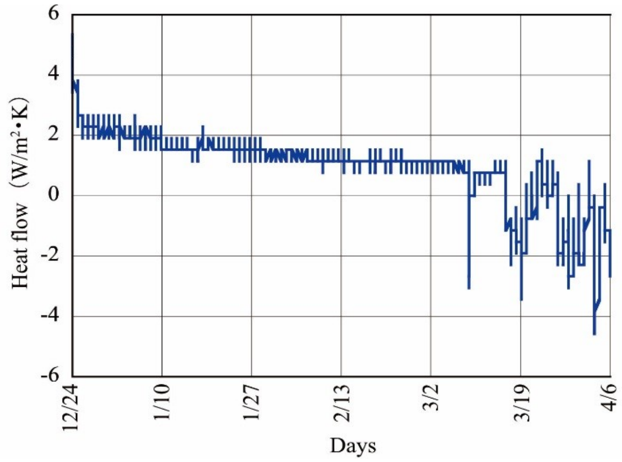

Figure 8. Heat flow rate of the ground surface

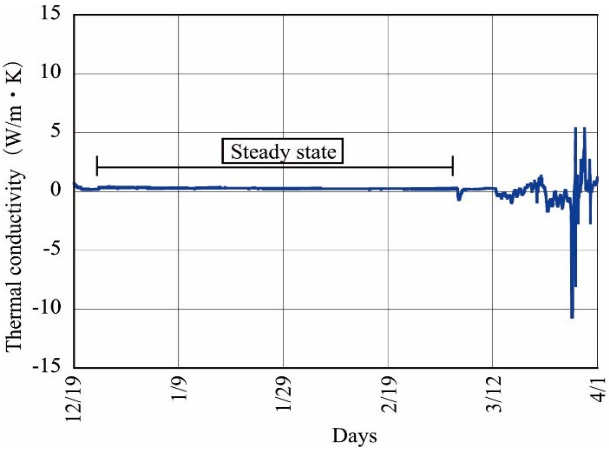

Figure 9. Change in thermal conductivity

3.2 *Thermal conductivity and heat flux of the local ground*

Figure 8 shows the heat flow rate of the surface at the local ground. It was measured by a heat flowmeter installed at a depth of 200 mm at the center of the slope surface. Also, changes in the thermal conductivity of the surface at the local ground are shown in Figure 9. This was calculated from the following equation (Nakayama et. al.2002) from the heat flow rate, the thickness of the soil layer, and the temperature difference between the both ends. In this figure, based on the average value of the steady part (December 25, 2014 - March 4, 2015), the thermal conductivity of the surface at the local ground was taken as 0.25 W/mK. The heat flux q_s flowing through the solid is

$$qs = \lambda_S \frac{dT}{dx} \tag{1}$$

$$qs = \lambda_S \frac{dx}{T_{S1} - T_{S2}} \tag{2}$$

Where, T_{S1} is the temperature at a depth of 350 mm of the surface at the local ground, T_{S2} is the temperature at a depth of 1050 mm of the surface at the local ground, λs is the thermal conductivity of the surface at the local ground, and q_s is the heat flux of the surface at the local ground.

3.3 *Analysis*

Table 4 shows the parameters used for the analysis. The heat transfer coefficient h from the air to the solid is 4.65 W/m^{2}K in the case of no wind, but here it is 10 W/m^{2}K in consideration of the case of gentle breeze or the like. Although it is difficult to set the emissivity, convection heat transfer becomes dominant because the heat transfer coefficient is relatively large, and the influence on the solution is small. Therefore, it was assumed to be 0.9 here. Reference value of manufacturer of the materials used in the experiment were used as the thermal conductivity of the thermal insulating materials. As the thermal conductivity of the ground, the value obtained from the heat flow rate and the temperature difference was used, both of them measured from the site.

With the above parameters fixed, the ground surface temperature T_2 is calculated by changing the temperature T_A and the thickness t of the heat insulating material.

3.4 *The required thickness of the thermal insulating layer*

Figure 10 shows the relationship between the thickness of the thermal insulation layer due to the outside air temperature and the ground surface, obtained from the method and conditions described above. The lowest air temperature obtained from the in-situ tests is about -7 degree Celsius. Also, the average daily air temperature in the coldest season is about -1 degree Celsius and the accumulated temperature of the air is about -2 degree Celsius. Therefore, if it is considered that outside air temperature at the site is -3 to -5 degrees Celsius, 45 to 75 mm becomes the heat insulating layer thickness necessary for the frost heaving measure. Similar results are obtained in the experimental, which can be said to be roughly reasonable.

Table 4. Parameters used for the analysis

The thickness of the soil layer	1m
Temperature at *ts* Ts	283K
Emissivity ε	0.6
Heat conduction coefficient *h*	10 W/m^{2}K
The thermal conductivity λ_I of the heat insulating material	0.039
Thermal conductivity of the ground λ_S	0.25

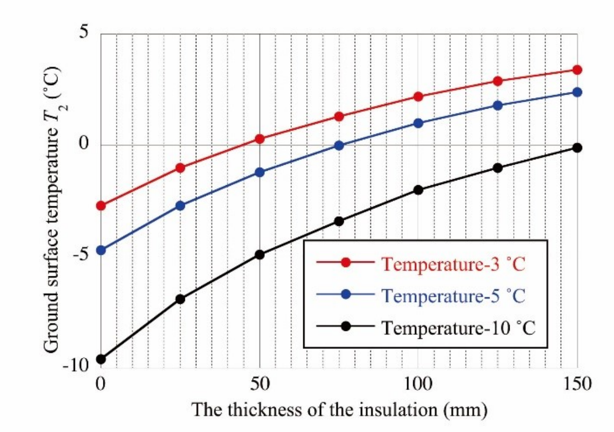

Figure 10. Outline of one-dimensional station-ary thermal conductivity

4 CONCLUTION

Based on the in-situ test and analysis results, the thickness of the thermal insulating materials necessary for frost heaving measures could be determined. By changing the parameters used for the calculation, it is possible to obtain the suitable thickness of the thermal insulating materials for the site where measures are required. It was also found that depending on the thickness of the geocell and the kinds of the filling materials used, it is possible to prevent or suppress the frost heave without using the thermal insulating materials. In the future, it is necessary to investigate the kind of filling materials and the thermal conductivity of each filling material by laboratory tests. It is also necessary to investigate the influence on the frost heave in a situation where the thermal insulation materials are not laid and the countermeasure methods which do not require the thermal insulating materials.

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