A STUDY ON USING WATERPROOF ASPHALT SHEETS TO MAKE FROST HEAVE-RESISTANT DRAINAGE DITCHES

T. Adachi[1], S. Nishimura[1], and A. Sato[1]
[1]Geotechnical Research Team, Civil Engineering Research Institute for Cold Region
Tel:+81-11-841-1709;Fax:+81-11-841-7333;Email:ziban511@ceri.go.jp

ABSTRACT

As the concrete products generally used for berm drains on cut slopes are not flexible, they are unable to mitigate the pressure of frost heaving force and are susceptible to related damage. However, the idea of using drainage structures to physically suppress pressure is unrealistic because frost heaving force is strong enough to push up a building. To ensure resistance to frost heaving, there is a need for materials that can change form flexibly and maintain drainage functionality under the influence of such force rather than drainage structures that can withstand it. Accordingly, test construction was conducted to determine the feasibility of using berm drains consisting of the type of waterproof asphalt sheets originally used for waste disposal and other purposes. This paper presents the results of an interannual survey based on visual and instrumental observation, which revealed that berm drains made from waterproof asphalt sheets fulfilled the requisite drainage function and offered a higher level of resistance to frost heaving than conventional concrete ditches. It was also found that asphalt sheets had a weed control effect and were suitable for berms on cut slopes that heavy machinery cannot reach because they are lighter and easier to install than concrete troughs.

Keywords: Frost heaving, frost penetration depth, frost heaving force, berm drain

INTRODUCTION

In recent years, breakage and damage to drains installed on berms of cut slopes have been reported in various areas of Hokkaido. Many such cases in cold regions are considered to result from frost heaving and freeze-thaw action. Although measures against frost heaving on such berms have been examined in past studies[1)], they have not been fully utilized because no guidelines or procedures for their implementation have been established[2)].

Berms placed halfway up slopes for stabilization and maintenance have shapes that allow more cold air to flow in from many directions than is the case with flat and sloped surfaces. As a result, drains installed on berms are susceptible to frost heaving damage.

As the behavior of frost heaving force is closely related to the development of freezing, it is assumed that berm drains are damaged by such force during freezing progression in which the freezing isotherm moves through the ground near them.

In this study, the effects of frost heaving force on berm drains was evaluated with a focus on freezing progression, and anti-frost heaving measures to combat these effects were analyzed.

MEASURES TO MITIGATE FROST HEAVING FORCE

Figures 1 and 2 show frost heaving damage to berm drains, and Fig. 3 illustrates approaches to preventing such problems.

There are two ways to prevent frost heaving damage. One is to actually prevent frost heaving, which occurs when certain criteria in relation to three considerations (i.e., soil quality, water content and air

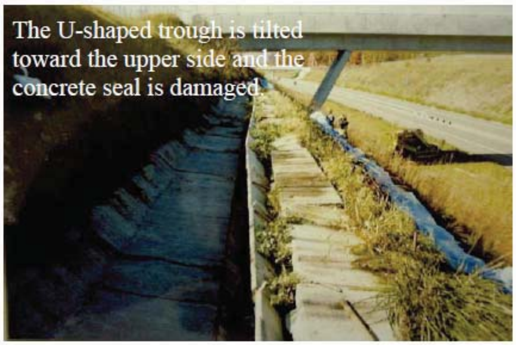


Fig. 1 Frost heaving damage to a berm on a cut slope

Fig. 2 Frost heaving damage to a berm on a cut slope

temperature) are met. If any one of these criteria is wrong, frost heaving does not occur[3].

Another approach involves the use of flexible structures to mitigate frost heaving force. The low-flexibility concrete products often used for berm drains on cut slopes[4] cannot mitigate such force and are susceptible to related damage. Against such a background, a flexible berm drain structure was considered and test construction was conducted in this study.

FROST HEAVING MECHANISM AND REGIONAL CHARACTERISTICS

Frost Heaving Mechanism

The frost heaving mechanism in ground is illustrated in Fig. 4. The ground surface temperature drops with reduced air temperature, and a freezing isotherm (the level at which freezing occurs) forms in the ground. At this time, water moves toward the isotherm from the non-frozen part of the ground, and when water collecting at the isotherm freezes, ice separates from the soil particle surface, thereby thickening the thin ice layer and pushing up the ground. This phenomenon of ice layer formation is called ice segregation, and the ice layers formed are called ice lenses. Thus, ice segregation caused by the freezing of water that moves to the freezing isotherm represents the mechanism behind ice lens formation.

As outlined above, ice lens formation itself underpins the frost heaving mechanism. However, the basic mechanism is extremely complex, and has not yet been fully clarified either physically or chemically[6].

Regional Characteristics and Distribution of Frost Heaving Damage

Figure 5 shows the main weather characteristics of different areas in Hokkaido[7]. Frost heaving in cold snowy regions tends to occur often in low-temperature and light-snow areas and less frequently in low-temperature and heavy-snow areas, probably because snow cover is closely related to the phenomenon's development. Snow acts as an insulator because it contains large volumes of air, and reduces the occurrence of frost heaving by controlling temperature – one of the three essential elements in frost heaving[8].

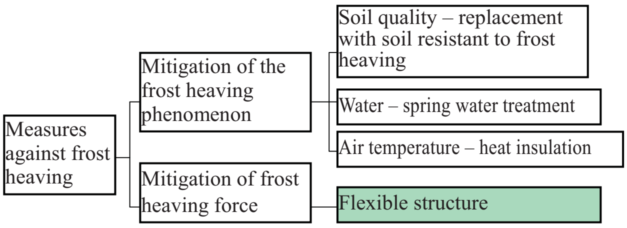


Fig. 3 Approaches to prevent frost heaving damage

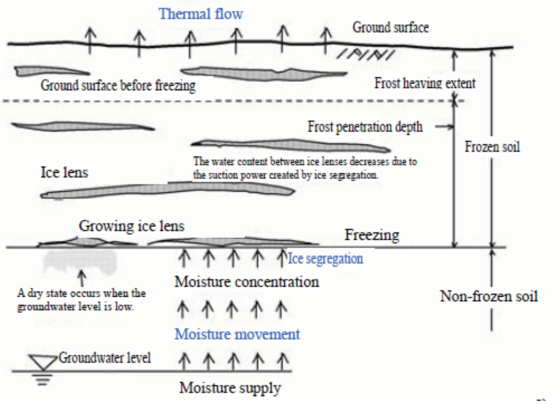


Fig. 4 The frost heaving mechanism in the ground[5]

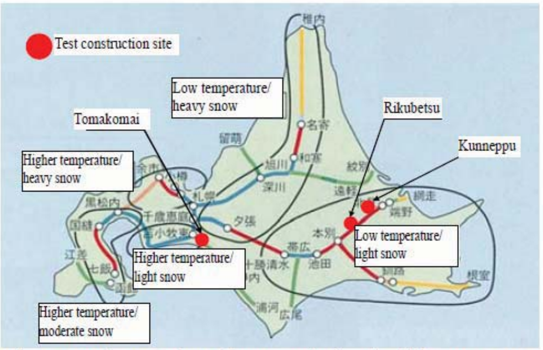


Fig. 5 Main weather characteristics in different areas of Hokkaido and the test construction sections (with additions made by the authors in relation to the figure in Reference[7])

Table 1 n-year probability freezing indices of the test construction sites[9] (°C/day)

	n-year probability freezing		Weather characteristics
	n=10	n=20	
Kunneppu	1010	1080	Low temperature/light snow
Rikubetsu	1250	1320	Low temperature/light snow
Tomakomai	370	410	Higher temperature/light snow

Table 2 Basic physical soil properties

Sample	Kunneppu	Rikubetsu	Tomakomai
Natural water content	32.72	27.26	46.98
Soil particle density (g/cm^3)	2.726	2.743	2.470
Liquid limit (%)	55.45	56.60	N.P.
Plastic limit (%)	29.91	29.61	N.P.
Plasticity index (%)	25.54	26.99	N.P.
Gravel (%)	42.2	37.3	22.8
Sand (%)	26.1	32.4	51.4
Silt (%)	5.0	7.6	25.8
Clay (%)	26.7	22.7	
Soil classification	Fine-grained sandy gravel (GFS)	Fine-grained sandy gravel (GFS)	Volcanic ash cohesive soil (SVG)

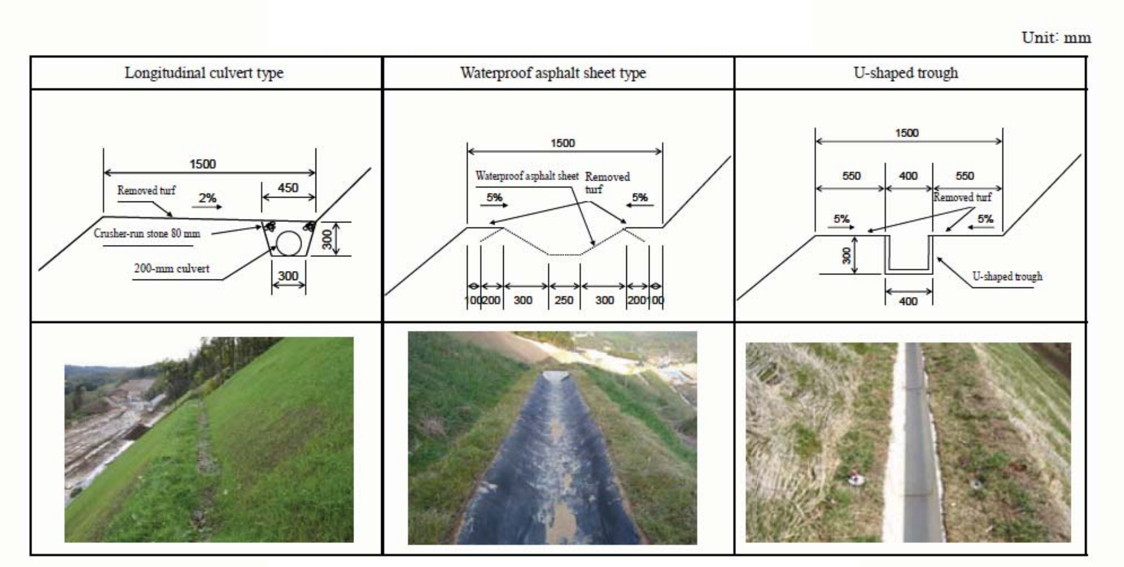


Fig. 6 The construction sections of berm drains

TEST CONSTRUCTION OVERVIEW

To evaluate how frost heaving force affects berm drains on cut slopes and to establish a drainage structure that will mitigate related damage, berm drain test construction was conducted using a flexible drainage structure to mitigate frost heaving force. Instruments to measure the earth temperature and the extent of frost heaving were also installed.

Test Construction Sites

Figure 5 shows the locations of the test construction conducted on road cut slopes in FY 2009 in Kunneppu and Rikubetsu, which are low-temperature, light-snow areas. Test construction was also conducted in FY 2010 at an on-site test field in Tomakomai (a higher-temperature, light-snow area) using an embankment slope to which water was supplied from the rear to simulate a cut slope fed with spring water.

Table 1 shows the n-year probability freezing indices[9)] at the test construction sites. Kunneppu and Rikubetsu are areas where the indices were especially high for Hokkaido. Table 2 shows the basic physical properties of the soils at the sites. Those at Kunneppu and Rikubetsu were deemed susceptible to frost heaving based on grain-size curves found via the frost heaving susceptibility test method. The susceptibility of the soil in Tomakomai was found to be moderate.

Test Construction Sections

In addition to the conventional U-shaped trough, two flexible drainage structure profiles were also used in the test construction. Figure 6 shows their cross sections and installation conditions.

(1) Longitudinal culvert-type berm drain
A flexible longitudinal culvert pipe was installed on the upper side of the berm to channel spring water from the slope and surface water, the latter of which was dealt with by applying a 2% inverse draft to the berm. The ground on the lower side was protected by sodding.

(2) Waterproof asphalt sheet-type berm drain
A flexible waterproof asphalt sheet was placed at the center of the berm, and surface water was dealt with by applying a 5% slope to the berm.

(3) U-shaped trough
A conventional U-shaped trough was placed at the center of the berm, and surface water was dealt with by applying a 5% slope to the berm. The ground on both sides was protected by sodding.

Fig.7 Instrument installation status

Study Method

To evaluate how frost heaving force affects flexible and conventional concrete berm drains, soil thermometers were placed to measure earth

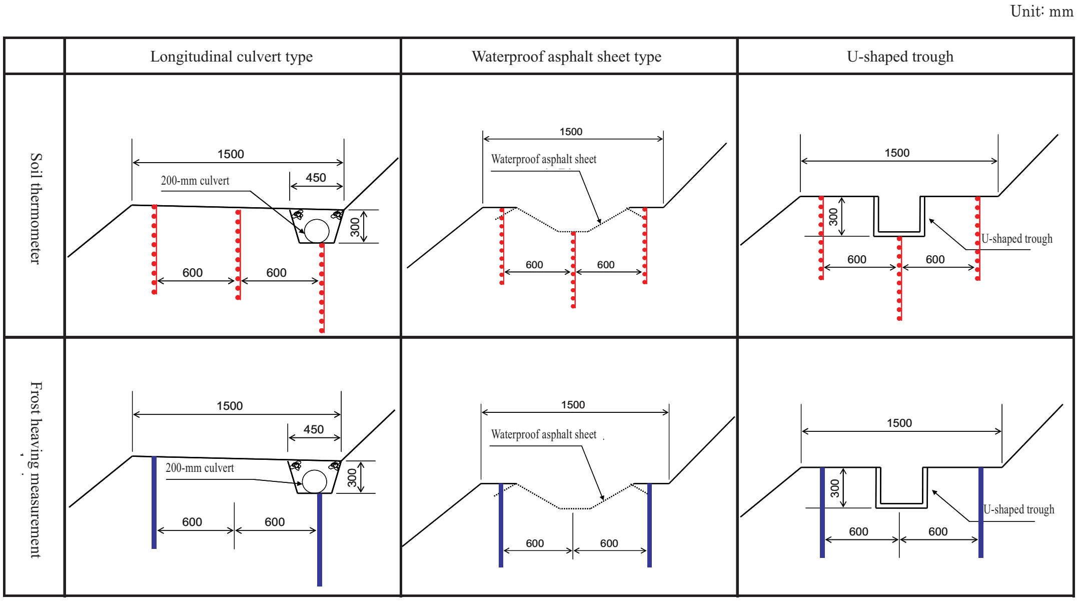


Fig. 8 Instrument positions

temperature at the test construction sites. Figure 7 shows the installation conditions of the frost heaving measurement devices and soil thermometers, and Fig. 8 shows their positions.

(1) Earth temperature/external air temperature measurement (Kunneppu, Rikubetsu, Tomakomai)

To evaluate the effects of frost heaving force, it is necessary to clarify the movement of the freezing isotherm. As shown in Fig. 4, its position (i.e., the frost penetration depth) strongly affects ice lens formation, and frost heaving force acts perpendicularly to it. The freezing isotherm is a level formed by joining points at which the ground temperature is 0°C, and can be found by measuring the earth temperature. Soil thermometers were placed at three points (the lower, middle and upper sides) of the longitudinal culvert-type, waterproof asphalt sheet-type and U-shaped trough drains to automatically determine the earth temperature. Automatic external air and ground surface temperature measurement was also conducted to find the freezing indices.

(2) Measurement of frost heaving extent (Tomakomai)

Frost heaving extents were determined using measuring devices to clarify their relationships with frost penetration depths. The devices were placed at two points (the lower and upper sides) of the three different types of drains.

TWO-DIMENSIONAL FEM HEAT TRANSFER ANALYSIS (TOMAKOMAI)

Two-dimensional FEM heat transfer analysis was conducted to complement the measurement results obtained during freezing progression, to clarify the behavior of the freezing isotherm in greater detail and to support evaluation of the effects of frost heaving force on berm drains.

Table 3 Heat conductivity of individual materials (W/m-k)

Material		Heat conductivity
Volcanic ash cohesive soil	Frozen soil	0.754
	Non-frozen soil	1.254
Crusher-run stone	Frozen soil	2.534
	Non-frozen soil	2.491
Concrete		0.938
Waterproof asphalt sheet		0.223
Snow		0.261

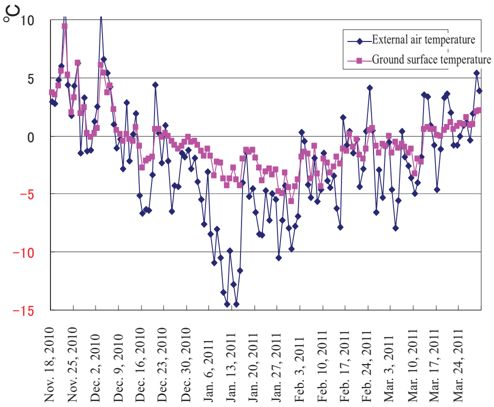


Fig. 9 External air temperature and ground surface temperature

Analysis Conditions

The behavior of the freezing isotherm was examined in detail by dividing the cross section of the berm part into 2,162 10-cm meshes and presenting daily temperature distributions.

Table 3 lists the heat conductivity values used for the analysis. Those for volcanic ash cohesive soil and crusher-run stone were found by dividing them into the values for frozen and non-frozen soils and using Kersten's experimental equation[11]. The conductivity of concrete and snow was found using commonly adopted thermal constants[12], and that of the waterproof asphalt sheet was found based on measurement.

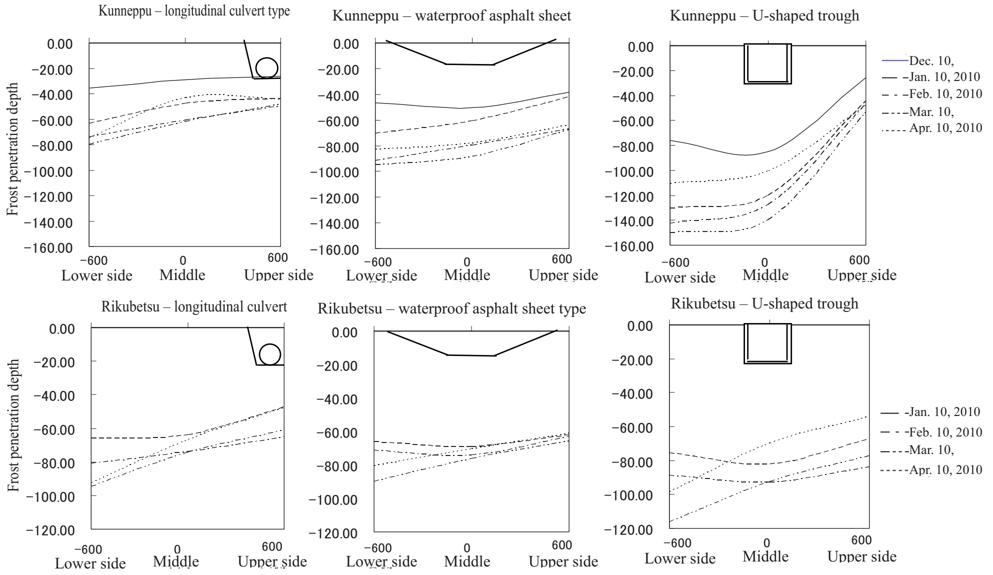


Fig. 10 Movement of freezing isotherms (Kunneppu, Rikubetsu)

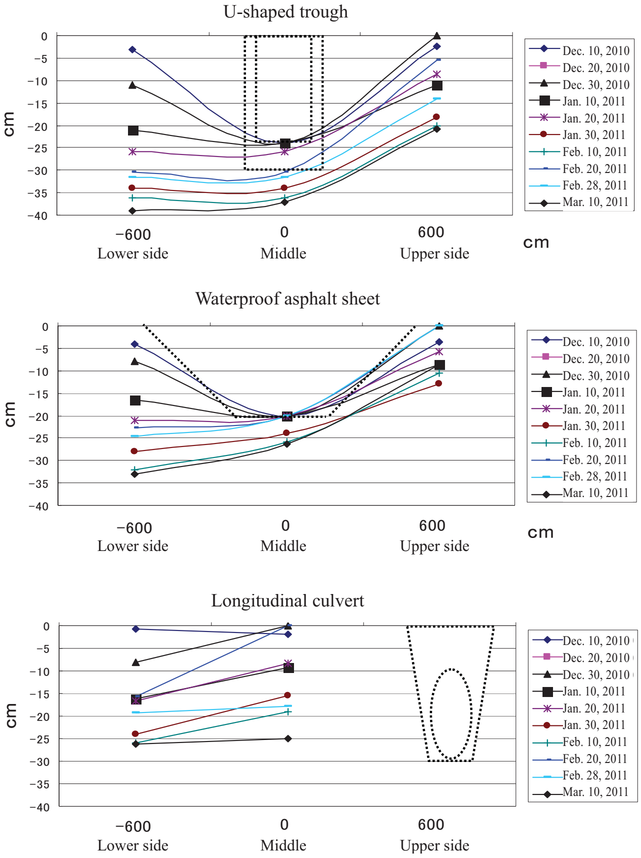


Fig. 11 Changes in the freezing isotherm during freezing progression (Tomakomai)

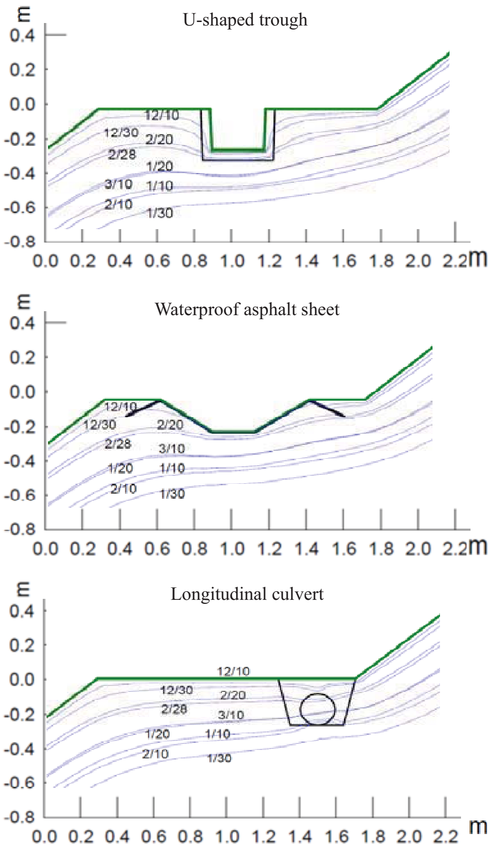


Fig. 12 Changes in the freezing isotherm as found from two-dimensional FEM analysis

Effects of Snow Cover

Figure 9 shows the measured values of external air temperature and ground surface temperature. It can be seen that the ground surface temperature was higher than the external air temperature in the freezing season. As this was considered to be due to the effect of snow cover, ground surface temperature was used for analysis in consideration of snow cover.

TEST RESULTS AND DISCUSSION

Earth Temperature Measurement Results (Kunneppu, Rikubetsu)

Figure 10 shows freezing isotherm behavior in Kunneppu and Rikubetsu as determined from the earth temperature measurement results. The frost penetration depth at the berm surface is shown as 0. It can be seen that when freezing progressed, the increase in frost penetration depth caused by the effect of cold air flowing in from the slope surface was greater in the order of the upper, middle and lower sides. Penetration was shallower for the waterproof asphalt sheet type and the longitudinal culvert type than for the U-shaped trough. The maximum frost penetration depths were reduced by 34 and 53% with the asphalt sheet and the culvert, respectively. It was assumed that the effect of cold air flowing in from the inner space was greater in the U-shaped trough.

Changes in the Freezing Isotherm in the Advanced Stage of Freezing (Tomakomai)

In the test construction in Kunneppu and Rikubetsu, the freezing indices were greater and freezing progressed more quickly. As it had already progressed to the level below the bottom of the drains when the soil thermometers were installed, the behavior of the freezing isotherm near the drains could not be determined. Accordingly, the effect of frost heaving force on berm drains was evaluated with focus on the freezing progression period based on the measurement results obtained from the soil thermometer in Tomakomai. Figure 11 shows changes in the freezing isotherm in Tomakomai. It can be seen that freezing progressed more quickly on the lower side than on the upper side due to the effect of cold air from the lower side. The progress of freezing was also faster and frost penetration was deeper in the order of the longitudinal culvert type, the waterproof asphalt sheet type and the U-shaped trough. This was thought to be due to the effect of cold air flowing in from the inner spaces of the drains. As the soil thermometer on the upper side of the longitudinal culvert type was placed at a level deeper than the culvert, the soil temperature did not fall below zero and the frost penetration depth at levels shallower than this could not be ascertained.

The above results confirmed that berm drains made from waterproof asphalt sheet or longitudinal culvert structures provide a greater reduction in the maximum frost penetration depth than U-shaped troughs.

Two-Dimensional FEM Heat Conductivity Analysis Results (Tomakomai)

Figure 12 shows the movement of the freezing isotherm based on two-dimensional FEM heat conductivity analysis. To take the effect of snow cover into account, the ground surface temperature was used for the analysis. It can be seen from the figure that, as with the measured values shown in Fig. 8, freezing progressed faster and the frost penetration depth increased in the order of the longitudinal culvert type, the waterproof asphalt sheet type and the U-shaped trough.

A clear difference was also seen between the

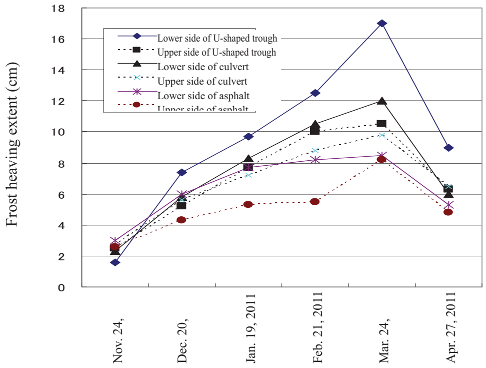


Fig. 13 Change in the frost heaving extent (Tomakomai)

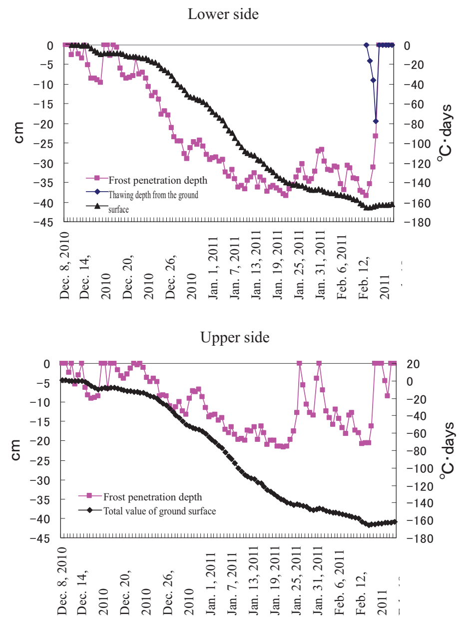
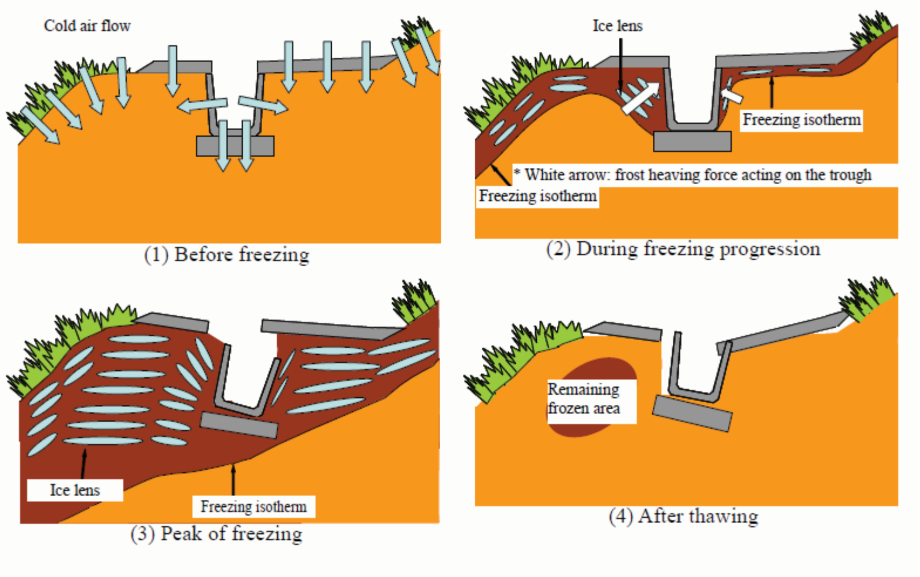


Fig. 14 Total value of ground surface temperature and frost penetration/thawing depths



(1) Before freezing
(2) During freezing progression
(3) Peak of freezing
(4) After thawing

Fig. 15 Evaluation of the effect of frost heaving force on the U-shaped trough

U-shaped trough and the asphalt sheet concerning the movement of the freezing isotherm during the development of freezing. In the case with the U-shaped trough, freezing progressed from the sides of the drain. As the frozen part near the sides became wider and deeper on the lower side than on the upper side due to the effect of cold air flowing in from the slope surface, the form of the freezing isotherm was non-symmetrical around the trough. As frost heaving force works perpendicularly to this isotherm, it acted on the sides of the trough in this case. Trough behavior in relation to this will be described in the next chapter.

This phenomenon was not seen in the case with asphalt sheet for two probable reasons. First, the side geometry of the drains was different; as the sides of the U-shaped trough were nearly vertical, part of it was exposed to cold air from multiple directions (i.e., the sides of the drain and the ground). The effect of cold air from the sides was small in the asphalt sheet-type drain, as its sides were almost horizontal. Second, cold air was more likely to flow into the U-shaped trough because its heat conductivity was approximately four times as high as that of the asphalt sheet.

Since the longitudinal culvert type, which had a flat structure without a ditch, was affected only by cold air from the ground, the frost penetration depth of the freezing isotherm simply increased from the upper to the lower side. It was therefore presumed that frost heaving force acting on the longitudinal culvert worked only in an almost-vertical direction.

The above results indicate that the effect of uneven frost heaving force acting on the drain itself was smaller for berm drains with a waterproof asphalt sheet or longitudinal culvert than for the U-shaped trough. That is, drains with flat cross-sectional shapes are less susceptible to uneven frost heaving force.

Frost Heaving Measurement Results

Figure 13 shows the frost heaving measurement results for Tomakomai. It can be seen that heaving was greater on the lower side than on the upper side due to the effect of cold air flowing in from the slope surface. Heaving was less extensive in the drains with an asphalt sheet or longitudinal culvert than in the U-shaped trough, probably due to the smaller effect of cold air from the drains and lower heat conductivity. The results were similar to those for frost penetration depth, and frost heaving was found to increase with greater frost penetration depth.

These results indicate that berm drains with an asphalt sheet or culvert reduce frost heaving more than the U-shaped trough.

Ground Surface Temperature and Frost Penetration Depth

Figure 14 shows the cumulative total value of ground surface temperature for the U-shaped trough, the frost penetration depth and the thawing depth from the ground surface in Tomakomai. It indicates the following:

- The frost penetration depth increased until mid-February, when the rise in the total value of ground surface temperature was significant.
- Subsequently, the frost penetration depth fluctuated until mid-March, when the rise in the total value of ground surface temperature stopped.
- When the above increase stopped in mid-March, the frost penetration depth suddenly decreased to zero and no more freezing was observed.

The progress of thawing from the ground surface was observed on the lower side of the berm in mid-March, but not on the upper side. While thawing progressed gradually around the U-shaped trough in the thawing season, a frozen area remained on the lower side of the berm.

EVALUATION OF THE EFFECT OF FROST HEAVING FORCE ON BERM DRAINS

Based on the above results of test construction/measurement and heat conductivity analysis, the effect of frost heaving force on the U-shaped trough was evaluated with focus on the period of freezing progression (Fig. 15).

(1) Before freezing

As temperature decreases, cold air flows into the ground. It is more likely to flow in cases with concrete troughs or seals, as their heat conductivity is higher than that of non-frozen soil.

(2) During freezing progression

Cold air in soil causes ground freezing and the formation of a subterranean freezing isotherm.

Water from the non-frozen part of the ground concentrates near this isotherm and forms ice lenses. The force generated by the expansion of these lenses is called frost heaving force, and works perpendicularly to the freezing isotherm. It acts on concrete troughs and seals, causing deformation.

Freezing progresses from non-frozen soil near the sides of the trough due to the effect of cold air flowing in from the sides, and a freezing isotherm forms around it. The frost penetration depth and frozen area become greater on the lower side of the trough than on the upper side due to the effect of cold air from the slope surface, and the freezing isotherm on the upper and lower sides of the trough becomes non-symmetrical. This makes the ice lens formation area on the lower side larger than that on the upper side of the trough, and the force of frost heaving on the trough from the lower to the upper side becomes greater than that acting on the trough from the upper to the lower side as shown in the figure, resulting in a deformation phenomenon in which the trough tilts toward the upper side.

(3) At the peak of freezing

When the freezing isotherm moves below the bottom of the U-shaped trough, it gradually becomes deeper toward the lower side due to the effect of cold air from the slope surface. It is therefore presumed that frost heaving force pushes up the ground, the concrete trough and seal are pushed up almost vertically, and the maximum displacement is reached at the peak of freezing.

(4) After thawing

In the spring thawing season, ice lenses melt, the entire berm becomes fragile and freezing remains only in part of the lower side. The concrete trough and seal that were pushed up settle vertically under their ownweight while maintaining a tilted position. In some cases, breakage may occur in steps (2) and (3) in addition to deformation.

Fig. 16 Weed control effect of berm drains

As detailed above, it was found that when frost heaving occurs on a berm of a cut slope, the U-shaped trough tilts toward the upper side due to the non-symmetrical conditions seen during freezing. This has been confirmed as an actual phenomenon, and is shown in Fig. 1 and 2.

WEED-CONTROL EFFECT OF BERM DRAINS

Frost heaving damage was actually prevented by using flexible berm drains, and waterproof asphalt sheets were also confirmed to have a weed control effect. Fig.16 shows the situation two years after the U-shaped trough and waterproof asphalt sheet were simultaneously installed. It can be seen that there are fewer weeds on the asphalt sheet than on the U-shaped trough. It is presumed that the embedded parts at both ends of the sheet prevented root growth. The sheet was also considered to provide a weed control effect as it covered the berm almost entirely. It can therefore be said that berm drains made with waterproof asphalt sheets are also effective in terms of facilitating maintenance.

CONCLUSIONS

The following findings were obtained from the results of the above instrumental measurement and heat conductivity analysis:

(1) On a berm of a cut slope, the frost penetration depth and frost heaving extent both increased in the order of the upper, middle and lower sides.

(2) The frost heaving extent increased with greater frost penetration depth.

(3) When frost heaving occurs on a berm of a cut slope, the resulting force acts on U-shaped troughs due to non-symmetrical freezing of the ground, causing the trough to tilt toward the upper side.

(4) Berm drains made using waterproof asphalt sheets or longitudinal culverts can reduce the maximum

frost penetration depth and frost heaving extent more than U-shaped troughs.

(5) Such berm drains are affected less than U-shaped troughs by uneven frost heaving force acting on the drains themselves.

FUTURE TASKS

This study's evaluation of the effect of frost heaving force on berm drains on cut slopes revealed that the flatness of cross-section structures and the flexibility of materials are significant in mitigating related damage. In the future, it will be necessary to conduct an interannual survey on frost heaving damage to confirm the long-term effect of frost heaving on berm drains with flat structures. As the effect of frost heaving force on other slope structures can also be evaluated by conducting similar analysis, such evaluation needs to be performed for slope structures that are actually vulnerable to frost heaving damage.

AFTERWORD

While past studies focused on low-temperature, light-snow areas that are often affected by frost heaving damage, this research revealed that small slope structures such as berm drains are also subject to such damage in a higher-temperature, light-snow area (Tomakomai) where the freezing indices are small and freezing isotherms progress slowly in shallow layers. It was found that flat berm drains on cut slopes were more effective in mitigating frost heaving force than conventional U-shaped troughs. Waterproof asphalt sheets were also found to have a weed control effect in addition to providing resistance to deformation caused by frost heaving.

The authors hope that the results of this study will provide a useful reference in measures against frost heaving on berm drains and for berm maintenance.

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