Factors causing deformation in embankments constructed in winter, and control measures

Facteurs provoquant la déformation des remblais construits en hiver, et mesures de prévention

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ABSTRACT: In Hokkaido and other cold, snowy regions, embankments constructed in winter can undergo deformation in the spring snowmelt period. To find techniques for controlling such deformation, a test construction was done. An analysis of the test construction found the following to be effective in controlling deformation. To prevent deformation in the snowmelt period, frost heave-resistant materials should be used. When frost heave-prone materials are used, the embankment should be constructed on a foundation of drainage material. When frost heave-prone materials are used, the number of stoppages in the work process should be kept as small as possible during construction. When a stoppage is inevitable, the surface of the embankment under construction should be covered with an insulating material. When it is difficult to cover the surface layer with an insulating material, construction of the next layer should be started after the frozen portions are removed. Frozen soil should not be used as an embankment material

RÉSUMÉ: À Hokkaido, comme dans les autres régions froides et enneigées, les remblais construits en hiver peuvent subir des déformations au printemps, durant la période de fonte des neiges. Une construction-test a ainsi été réalisée pour trouver les techniques qui permettraient de prévenir ces déformations. Une analyse de la construction-test a montré l'efficacité des points suivants dans la prévention des déformations. Pour éviter les déformations durant la période de fonte des neiges, il faut utiliser des matériaux résistants aux soulèvements dus au gel. En cas d'utilisation de matériaux propices aux soulèvements dus au gel, le remblai doit être construit sur une fondation de matériaux de drainage. En outre, si de tels matériaux sont utilisés, les pauses lors de la construction doivent être le moins nombreuses possibles. S'il est nécessaire de faire une pause, la surface du remblai en construction doit être couverte d'un matériau isolant. S'il n'est pas possible de protéger la couche en surface avec un matériau isolant, il faudra commencer la construction de la couche suivante après avoir enlevé les parties gelées. Il ne faut surtout pas utiliser de sol gelé en tant que matériel de construction du remblai.

KEYWORDS: embankment, winter construction, control measure

1 THE PURPOSE OF THIS STUDY AND AN OUTLINE OF THE PAPER

In Hokkaido and other cold, snowy regions, embankments constructed in winter can undergo deformation in the spring snowmelt period (Hokkaido Branch of the Japanese Geographical Society 2010, 2009). Because of this, winter construction has not been active in these regions in recent years. However, winter execution of earthworks is sometimes unavoidable due to the construction sequence or when disaster-relief work is necessary. Therefore, the establishment of winter construction techniques that mitigate deformation in the thawing period is called for. The authors investigated the frost heaving susceptibility of embankment materials and the inclusion of frozen soil blocks that occurs during construction as factors that contribute to the deformation of embankments constructed in winter. The influence of these two factors on the deformation of embankments was clarified, and laboratory tests and experimental constructions were done to determine techniques for mitigating embankment deformation during the thawing period (Atsuko Sato, Takahiro Yamanashi, Teruyuki Suzuki and Shinichiro Kawabata 2013, 2014). This paper summarizes the results.

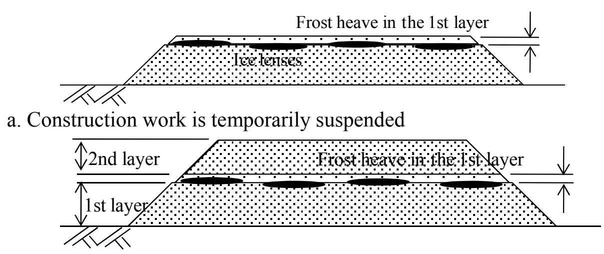


Figure 1. Causal factors for deformation in winter construction

2 FACTORS CAUSING DEFORMATION IN EMBANKMENTS CONSTRUCTED IN WINTER, AND COUNTERMEASURES

2 .1 *Factors causing deformation*

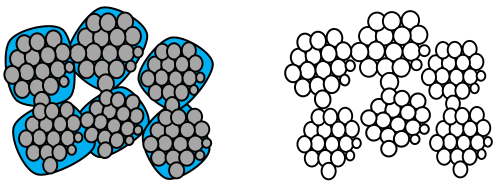
Unlike summer construction, winter construction is done under cold weather, and the constructed embankments tend to undergo deformation. The following are thought to be the causal factors of such deformation.

2.1.1 *Frost heaving during construction*

When the surface of the constructed layer of the embankment is exposed to cold air, ice lenses form in the upper part of the layer (Fig. 1a). If the height of the layer exposed to the cold air is low or the groundwater level is high and the embankment material is highly frost-heave susceptible, many ice lenses form, and the frost heave becomes considerable. In constructing the next layer, the layer ends up being thinner than the planned thickness because of the increased thickness of the underlying layer, which becomes thicker than the planned thickness from frost heave (Fig. 1b). If the surfaces of the embankment layers freeze during winter construction, the height of the completed embankment is lower than the originally planned height by as much as the combined thicknesses of frost heave in the layers. Frost heave occurs in random locations, which causes unevenness in the surface of the embankment after thawing. Furthermore, the volume of an embankment that has undergone frost heave becomes large and the density of the material becomes low. The decrease in density from frost heave does not return to that at construction completion, and this is thought to be a reason for the decrease in the embankment strength.

2.1.2 *Inclusion of snow and frozen soil*

If blocks of snow are mixed in the soil material of an embankment, and the snow in the embankment melts in early spring, the parts where the snow blocks were remain as voids. As shown in Fig. 2a, frozen soil particles are consolidated and appear similar to solid rocks. These pseudo-rocks have high strength and are not crushed at the compaction energy exerted at rolling compaction during embankment construction but are included in the embankment body without losing their shape. When the embankment starts to thaw in spring (Fig. 2b), the soil particles in the frozen blocks start to lose their cohesiveness, and low-density masses of particles occur. As a result of the thawing of frozen soil blocks in the embankment, the embankment subsides after thawing, and the embankment strength decreases.



a. Frozen b. Thawed

Figure 2. Frozen soil particles in a compacted

2.2 *Countermeasures*

The three factors that contribute to frost heaving are freezing temperatures, soil of a quality susceptible to freezing, and high moisture content (The Japanese Geotechnical Society 2009). When all three factors are present, frost heave occurs. The elimination of even just one of these three factors can control deformation from frost heave. The inclusion of snow and frozen soil in the embankment during winter construction can be avoided if visual checks and removal are done.

3 CONSTRUCTION AND INVESTIGATION METHODS

3.1 *Construction method*

The following techniques for controlling the deformation of embankments constructed in winter were tested: 1) the blocking of water intrusion into the embankment through the basement layer, 2) the use of materials that are not susceptible to freezing, 3) the prevention of embankment freezing, 4) construction in which the frozen surface layer is removed before a new layer is added, and 5) reduction in the number of work recesses per day of construction. The purpose of 5) is to reduce the number of frozen layers by reducing the number of work recesses during construction. Two embankments were constructed with frozen soil, and they were compared with two embankments constructed in summer. The tests were done at the Construction Test Field in Tomakomai City, Hokkaido, northern Japan. Each test embankment was constructed with a slope gradient of 1:1.5 and a height of 1.8m (Fig. 3). The materials are listed in Table 1. Material #1 contained 2.1% or less fine fraction, which is regarded as a material that is not susceptible to freezing in Japanese standards (Japanese Society of Soil Mechanics and Foundation Engineering 1994). Materials #2, #3, and #4 are regarded as frost-susceptible materials in the standards of the Japanese Geotechnical Society (The Japanese Geotechnical Society 2009). Each test embankment was constructed in 6 layers. The thickness of each layer after compaction was set as 30cm. To block water intrusion from the bottom of the embankment body, which would occur at freezing, the embankments were constructed on a foundation layer of 0.5m in thickness made with material that is not susceptible to freezing of 0 - 80mm class

Figure 3. Embankment shape

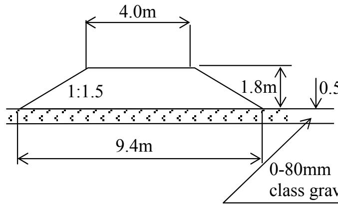


Table 1 Basic physical properties of the embankment materials

Embankment materials	1	2	3	4
Frost-susceptibility	Non-frost susceptible	Frost-susceptible		
Soil particle density ρ_s (g/cm^3)	2.745	2.626	2.546	2.732
Natural water content w_n (%)	9.2	40.5	67.9	68.6
Classification symbol of the ground material	GS	S-FG	SFG	SF
Max. dry density ρ_{dmax} (g/cm^3)	2.064	1.270	0.989	0.995
Optimum moisture content w_{opt} (%)	8.8	35.0	53.2	54.2
Cone index q_u (kN/m^2)	>2000	1403	509	649

Table 2 Construction periods and cumulative daily average temperature

Construction period	Absolute value of cumulative daily average temperature (°C･days)
Jan. 23, 2014 - Jan. 31, 2014	302.4
Feb. 5, 2013 - Feb. 19, 2013	158.1
Jan. 16, 2014 - Feb. 1, 2014	293.4

The absolute value of cumulative daily average temperature is the sum of values tallied from the first day of construction.

Table 3 Target frost-heave factors and anti-frost-heave measures

	Target frost-heave factor	Anti-frost-heave measure	Test location	Materials
1	Moisture	Blocking of water intrusion into the embankment	Laboratory	2, 3, 4
2	Soil quality	Construction using non-frost-heaving material	Onsite	1
3	Freezing temperature	Covering of the embankment with an insulating material	Onsite	2
4		Removal of the frozen portion	Onsite	2, 3
5		Reduction in the number of work recesses during construction	Onsite	1, 2, 3, 4

Construction of the embankments was done over the course of three years. The periods for construction and the cumulative daily average temperatures are shown in Table 2. The target frost heave factors and the anti-frost heave measures taken are shown in Table 3.

In the test case in which the embankments were covered with an insulating material, the embankment surfaces were covered with insulating materials (XPS) with 0.033×10^{-6}(W/m･K) in thermal conductivity and 5cm in thickness during the work recesses. For the embankments where the layers were constructed after removal of the frozen surfaces, a backhoe was used to remove the layers that froze during the night recesses. The surface of the layer whose frozen part was removed was roll-compacted before the next layer was constructed.

3.2 *Survey method*

For each embankment, air temperature and embankment internal temperature were measured. The embankment height was measured during and after construction. The density of the materials was measured for the embankment constructed using frozen soil and for the embankment constructed in summer.

4 MEASUREMENT RESULTS

4.1 *Frost susceptibility of the embankment materials without water supply*

It was thought that, even if the embankment materials were frost-heave susceptible, embankment deformation in the thawing period would be small if there were no water intrusion from the bottom of the embankment. The amount of frost heave was expected to be small without water intrusion. Based on the frost-heave experiment method of the JGS[5]), closed-system freezing tests and open-system freezing tests, in which only the water supply conditions differ, were done in the laboratory. The test results are shown in Table 4. In the JGS method, the frost-heave susceptibility is determined to be high when the frost-heave speed is 0.3mm/h or greater. Under the open-system conditions, the frost-heave speed is 0.3mm/h or greater for all the materials. The materials were all determined to be those with high frost susceptibility. In contrast, under the closed-system conditions, the frost-heave speed and frost heave ratio were low. Embankment material #2 is determined to be a material with high frost heave susceptibility in the ordinary frost-heave test; however, it was found to be a material with low frost-heave susceptibility under the closed-system conditions. The above test demonstrates that water supply greatly affects the degree of frost heave of materials. The embankment construction technique in which water intrusion from the bottom of the embankment was controlled was found to be promising in controlling frost heave.

Table 4 Frost heave of embankment materials with versus without water supply

Water supply	Embankment materials	2	3	4
With	Frost heave speed (mm/h)	0.387	0.660	1.205
	Frost heave ratio (%)	27.4	116.6	67.2
Without	Frost heave speed (mm/h)	0.045	0.256	0.262
	Frost heave ratio (%)	0.0	14.0	9.86

4.2 *Frost heave of embankments constructed using non-frost heaving material and of embankments on which insulation was used*

Fig. 4 shows the amount of deformation that occurred during the night work recesses for the embankments constructed using non-frost heaving material, embankments constructed by using insulation, and embankments without any frost heave countermeasures. In all three cases, construction was done by completing one layer per day. Slight subsidence was observed in the case with insulation. The embankments constructed using non-frost heaving material #1 showed no noticeable deformation except for the 5th layer. The embankments without any frost-heave countermeasures were found to have frozen during construction, and had frost-heave in all 5 layers. The amount of frost heave differed by layer because of differences in the night temperatures. The total frost heave was 75mm for the 5-layer embankment of 1.5m in height. The embankment with 75mm of frost heave has the potential to deform after thawing. Deformation of the embankments constructed with the non-frost heaving material and deformation of the embankments covered with insulating material were much smaller than deformation of the embankments constructed in winter without countermeasures. These two countermeasures are highly effective.

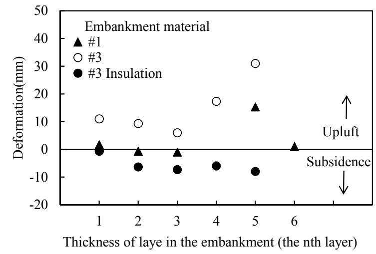


Figure 4. The amount of deformation from night work recesses

4.3 *Conditions of freezing inside the embankment*

Based on the temperatures measured inside the embankment, the parts of the embankment where the temperature would be below zero were estimated. The conditions of freezing in the embankment were determined for each day of observation. Fig. 5 shows the conditions of freezing of the embankments constructed using material #2. The numbers of layers constructed per day were 1, 2, and 6. Each embankment had as many frozen layers as days of construction. One frozen layer was formed after each work recess. The fewer the number of layers constructed per day, the greater the number of frozen parts near the bottom of the embankment and the greater the frost penetration depth. Because of the deep frost penetration of the embankments constructed over the course of more than 1 day, the periods for thawing were long. To control embankment freezing during winter construction, it is effective to construct as many layers as possible in one day and to avoid freezing at the borders between the roll-compacted layers.

4.4 *Embankment deformation*

To investigate the freezing-related deformation of the embankments, the height of each embankment crown was measured from construction completion to the end of the thawing period. Fig. 6 shows the freezing conditions of the 1-day and 6-day embankments constructed using material #4. For the 1-day embankment, the crown gradually rose with decreases in air temperature. Two weeks after the air temperature rose from the minus region to the plus region, the embankment

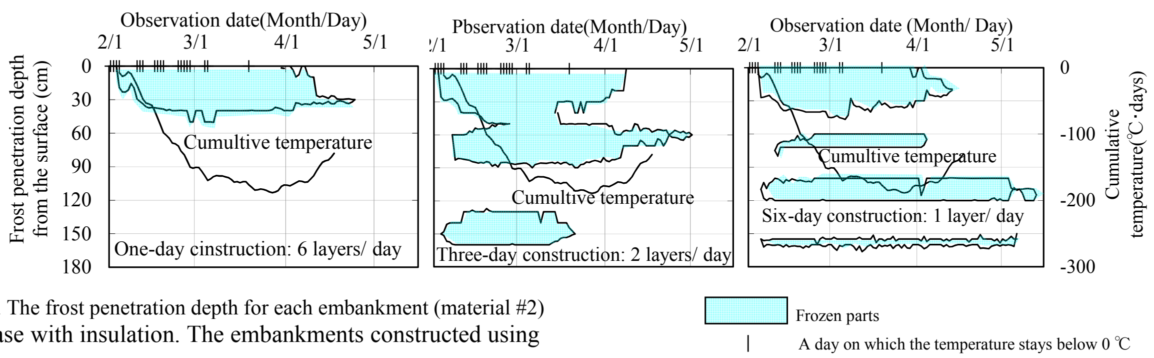


Figure 5. The frost penetration depth for each embankment (material #2)

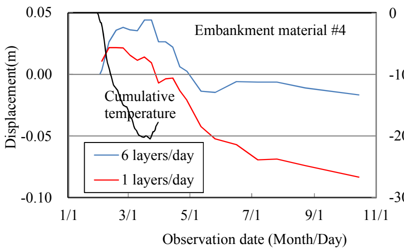


Figure 6. Embankment deformation from freezing and thawing

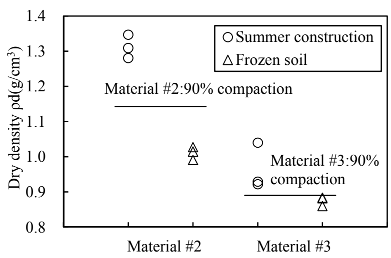


Figure 7. Dry densities of embankment materials used in the form of frozen soil

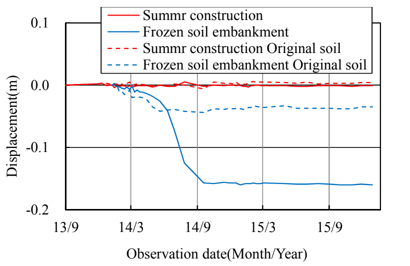


Figure 8. Deformations of embankment materials used in the form of frozen soil

started to subside. The crown height was about the same after complete thawing as at construction completion. Subsidence of the crown came to an end in mid May. The crown of the 6-day embankment rose slightly with the low temperature and then started to subside. This subsidence was found to still be in progress in mid October. When the surface of layers of an embankment that is constructed with frequent recesses freezes during recesses with low temperature, the embankment may continue to deform for a long period.

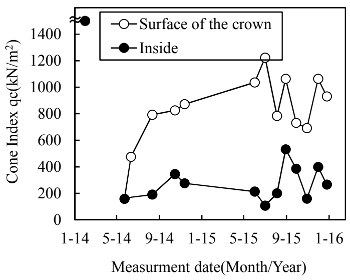


Figure 9. Strength of the embankment constructed using frozen soil

4.5 *Adverse effect of inclusion of frozen soil*

The dry densities of materials #2 and #3 in the embankments constructed in winter and in the embankment constructed in summer are shown in Fig. 7. Materials #2 and #3 used in winter construction were in the form of frozen soil. Materials #2 and #3 had standard values (Hokkaido Regional Development Bureau, Ministry of Land, Infrastructure 2016) and the degree of compaction of 90% or higher in the embankment constructed in summer. However, the dry densities of these materials used in the form of frozen soil were low and the degree of compaction did not satisfy the required values.

The embankment heights were measured. As an example to show deformation, the deformation of an embankment constructed using material #2 is shown in Fig. 8. The subsidence of the embankments constructed in summer was very small. The subsidence of the embankments constructed using frozen soil was great, and it continued up to about 10 months after construction. The original ground where the embankments were constructed had a similar subsidence tendency to that of the embankment constructed using frozen soil. The subsidence of the original ground progressed until July, and the final subsidence was 4.5cm. From the above, it is clear that embankments constructed using frozen soil on frozen ground greatly subside and take a long period until the end of the subsidence.

For use as an index of the strength of the embankment constructed using frozen soil, the cone index was measured. The changes in the cone indexes of the top surface and inside (30cm in depth) of an embankment are shown in Fig. 9. The surface of embankment after completion was frozen, and cone penetration was not possible. In early May, when thawing started, the cone index of the embankment surface was around 150kN/m^2. Walking on the embankment crown was not easy. After some time, the cone index of the embankment crown increased because of compaction from repeated rainfall and drying.

The cone index of the inside of the embankment was about 200kN/m^2 to 600kN/m^2 even after several months. For the embankment constructed using frozen soil, even when the strength at the surface became high, the strength inside the embankment was low. The stability of the frozen soil embankment remained questionable. The cone index of the embankment constructed in summer was very high and cone penetration was not possible at construction completion. When constructing embankments, the use of frozen soil must be avoided.

5 CONCLUSIONS

The experiment revealed that, even in winter construction, it is possible to reduce or eliminate deformation of embankments by using the following techniques: using non-frost heaving materials; when using frost-susceptible materials, blocking water intrusion from the bottom of the embankment; reducing the number of work recesses during construction as much as possible; and if work recesses are inevitable, covering the embankment under construction with insulating materials. When it is difficult to cover the surface layer with an insulating material, construction of the next layer should be started after the frozen portions are removed. Frozen soil should not be used as an embankment material.

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