CAUSE ANALYSIS OF SNOWMELT-INDUCED EXPRESSWAY SLOPE FAILURE THROUGH LABORATORY TESTING

Kazuhiro Tsuchiya

Maintenance Department, Hokkaido Branch,
Japan Highway Public Corporation
Tél.: +81-11-896-5211 / Fax: +81-11-896-5888
E-mail: Kazuhiro_Tsuchiya@gw.japan-highway.go.jp

1. Abstract

Snowmelt in early spring is one cause of slope failures and landslides in snowy regions. The infiltration of meltwater into a cut slope along an expressway plays a critical role in reducing resistance to sliding. Despite its significant impact on snowmelt-induced slope failure, snowmelt runoff process has not been discussed in most specifications.

Through simple laboratory testing on snowmelt and observation of snowmelt processes in the natural topography, this paper examines the case of a recent cut slope failure in the Hokkaido Expressway in the snowmelt season, and describes how snow melts and how meltwater infiltrates the ground to destabilize the cut slope.

Snowmelt runoff tests were conducted both inside and outside the laboratory, focusing on the fact that when a small snow block melts, meltwater drips only from the lowest part of the block. As part of the laboratory tests, snow blocks were placed on two slopes made of sandy soil. While one slope was completely covered with snow blocks, the other slope was covered only the upper part of it. As the result of the tests in the former case, meltwater moved downslope and flowed out from the snow layer, leaving the soil slope in a sound condition. In the latter case, meltwater flowing out of the lowest part of the snow layer infiltrated into the sandy soil, resulting in a failure.

Snowmelt processes similar to those observed in the laboratory tests can be seen on natural slopes. Since the site of the expressway cut-slope failure mentioned above is located at the lower end of a snow-covered area of an expressway cut slope, it can be inferred that phenomena similar to those observed in the laboratory tests occurred at the slope failure site.

2. Introduction

On April 13, 1999, a large-scale cut-slope failure occurred in the Kuromatsunai area in the Oshamanbe-Abuta section of the Hokkaido Expressway in the second snowmelt season after the expressway route opened (Figures 1, 2, and 3). The volume of the displaced material was approximately 7000 m^3, which is unprecedentedly large for a slope failure due to snowmelt.

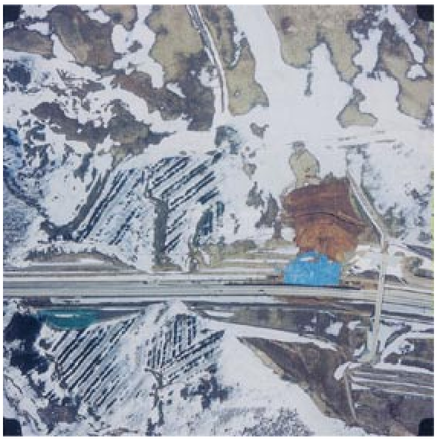

Figure 1 Kuromatsunai area and slope failure site (April 15, 1999)

Kuromatsunai is situated in a heavy snow area, where the total snowfall in a single winter season usually exceeds 10 m. The upper slope area is a vast expanse of grassland used for grazing, covered with heavy snow. It is believed that the cut slope failure was caused by a sharp increase in the amount of meltwater resulting from the topography conducive to concentration of snowmelt of grassland and from sharp temperature rises before the disaster.

When analyzing a slope failure due to snowmelt, it is necessary to verify snowmelt phenomena from two points of view: how snow melts and how meltwater infiltrates into the ground to destabilize the slope. Analysis of snowmelt phenomena requires detailed investigations of factors affecting the melting of snow, such as atmospheric temperature and solar radiation. However, in this study the snowmelt process is considered not from the standpoint of glaciology, but from observing natural snowmelt phenomena, and from laboratory and outdoor testing.

Figure 2 Slope failure site (Under construction)

Figure 3 Slope failure site (After reconstruction)

3. Laboratory tests on snowmelt phenomena

In order to infer how meltwater runs off during snowmelt, several laboratory tests were conducted. The ambient temperature in the laboratory was about 22°C. The following tests were conducted using snow samples taken in late March and mid-April, toward the end of the snowmelt season.

3.1 Laboratory test on snowmelt phenomena

Small blocks were placed on wire netting and were observed as they melted under laboratory conditions. In the test, as long as the snow blocks were inclined, however slightly, meltwater seeped downslope through the snow blocks and dripped down from the lowest part of the snow without dripping down from intermediate parts of the snow blocks (Figure 4). Similar tests were conducted

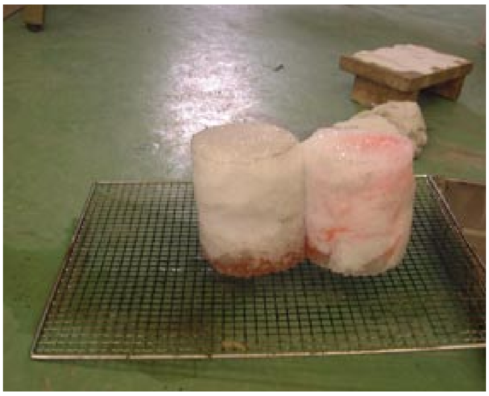

Figure 4 Meltwater dripping from lowest point of snow block

Figure 5 Snow-on-wire-netting test (before test)

outdoors in the sun, and similar results were obtained.

From these facts, it was suspected that as long as the snow layer was continuous, meltwater would move downslope through the snow layer until it flowed out from the lowest part of the snow layer.

To test this hypothesis, a snow slope on wire netting was prepared in the laboratory. The melting process was observed and meltwater runoff was measured. The snow slope was about 1.6 m long, and its gradient was about 8%. A continuous snow layer was formed by placing snow blocks on the wire netting. Blocks of granular snow measuring 3 cm in depth, 18 cm in width and 23 cm in length were used (Figure 5). In the experiment, the following were observed:

· Snowmelt runoff at the lower end of the slope was close to 100% of the total amount of meltwater (Figure 6).

· After 50 cc of water was sprinkled over the snow, meltwater runoff at the lowest part of the snow layer increased temporarily, but there was no vertical flow of water from intermediate parts of the snow layer. The time consumed for snow to melt showed no significant differences (Figure 7).

· It was only when the snow layer became thin and continuity of the snow blocks was lost that meltwater dripped down from parts of the snow layer other than the lower end.

These laboratory test results indicate that meltwater in a continuous layer of snow flows downslope through the snow layer and flows out from the lower end of the layer.

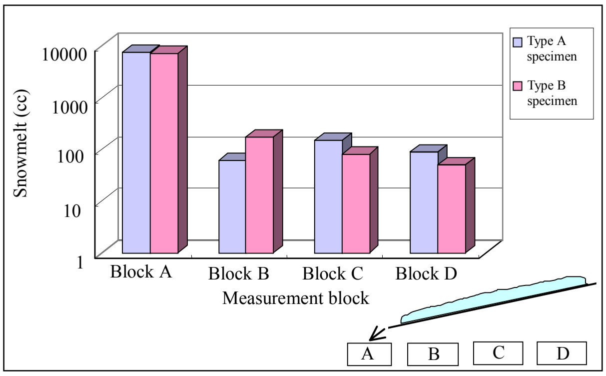

Figure 6 Snowmelt runoff by block

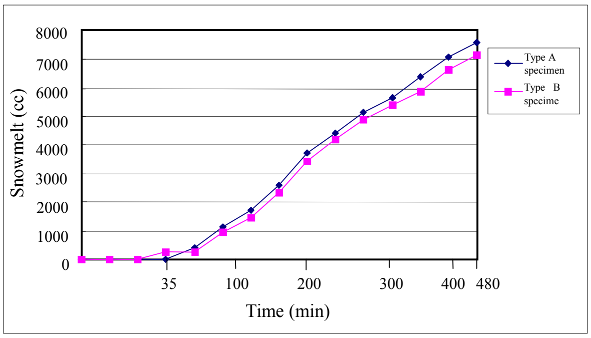

Figure 7 Changes over time in snowmelt runoff at lower end

3.2 Outdoor test

Snowmelt rates under indoor conditions, where temperatures are high but there is no solar radiation, differ from those under outdoor conditions, where temperature is low but there is solar radiation. Therefore an outdoor snowmelt test was conducted. A 7-m-long wire netting slope set at an inclination of 7% was used. The snow used in the test was granular, heavy snow taken at a late stage of the natural snowmelt process.

In the test, in the evening or morning hours when temperatures were low, meltwater seeped through the near-bottom region in the snow layer and flowed out from the lower end of the layer (Figure 8). However, as temperatures rose and solar radiation increased in the daytime, the snow became slushy. As a result, snow began to dangle through wire net openings as the snow melted, and meltwater began to drip down from several locations (ambient temperature: 5-6°C).

Under the indoor conditions, the room temperature was high, but convective currents of air were weak. Consequently, the snowmelt rate remained nearly constant. Under the outdoor conditions, snow melted quickly under the influence of solar radiation and wind because the snow blocks used in the test had a small cross section. This is thought to be why the outdoor test results differed from the indoor test results. Basically the temperature of the underside of the snow layer on the earth remains at 0°C. It may be that snowmelt phenomena similar to that observed in the laboratory test occurred on the natural slope.

Figure 8　Outdoor experiment

3.3 Snow-on-soil test

On the basis of the results of the snow-on-wire-net tests, tests were conducted to investigate differences between the snowmelt runoff in the case where a soil layer is covered with snow and that in the case where such a soil layer is not covered with snow. It was suspected that if meltwater flowed through the snow layer, meltwater would not infiltrate the soil.

3.3.1 Sandy soil

The soil layer used as the test specimen measured 15 cm (width) ∞ 15 cm (depth) ∞ 60 cm (length). The test specimen was compacted to a degree necessary to prevent it from collapsing. The initial water content was 37%.

-A test: The test specimen was covered with snow so that meltwater drips directly onto the test specimen (Figure 9; hereafter in this paper called "A test").

-B test: The top and front face of the test specimen were covered with snow (Figure 10; "B test").

In the A test, meltwater flowing out of the lower end of the snow layer infiltrated into the test specimen, resulting in a failure two and a half hours later (Figures 11 and 12). The process leading up to the failure is shown in Table 1.

Figure 9　Snowmelt test using soil specimen (left: A test, right: B test)

Figure 10　B test (end of snow layer outside test specimen)

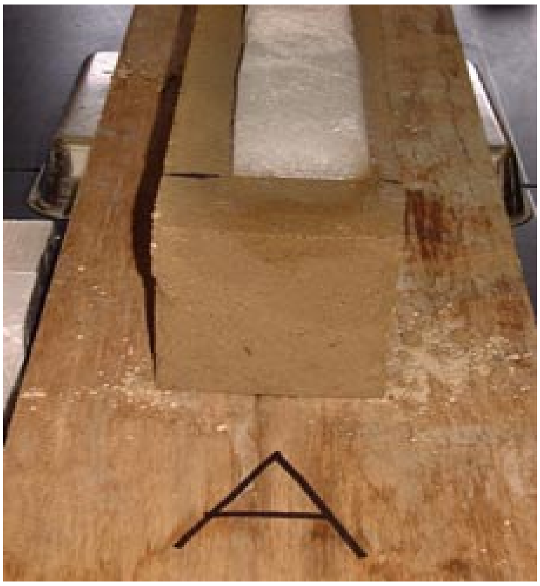

Figure 11　A test(10 minutes passed)

Figure 12　A test (2 hours 30 minutes passed)

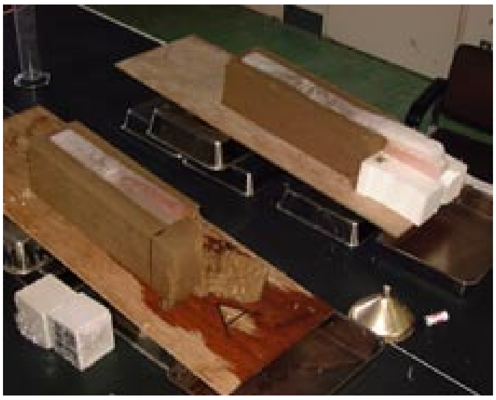

Figure 13　Drainage of meltwater

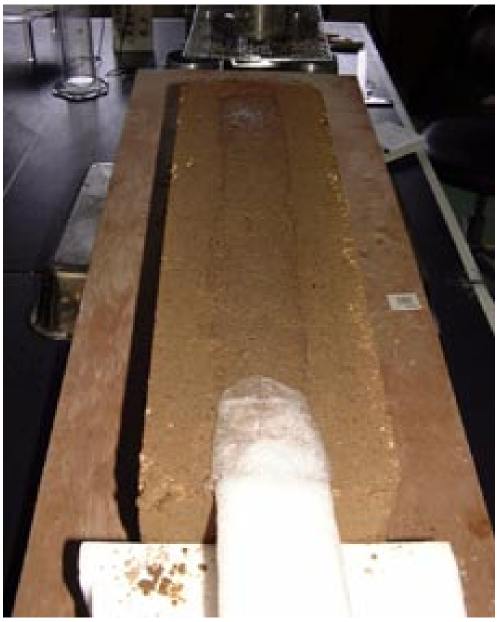

Figure 14　B test (3 hours 30 minutes passed)

In the B test, meltwater flowed out from the front-end part of the snow layer, and the test specimen was in a sound condition even after the snowmelt process ended (Figures 13 and 14). Measurement of the weights of the test specimens showed that the amount of infiltration into the test specimen was 40 cc, which is about 3% of the total volume of meltwater (Table 2). In the cases where red ink was introduced from the upper end of the snow-block layer, meltwater was observed to flow downslope along the bottom of the snow layer and flow out from its lower end. After the snow on the test specimen in the B test disappeared, a snow layer twice as thick as the first snow layer was placed on the test specimen, and the snowmelt test was continued. In this test, the test specimen remained in a sound condition, and heaving of side faces did not occur. The weights of the test specimens did not change, indicating that infiltration into the test specimens did not occur even when the volume of snow was doubled.

Table 1 Failure process

Time	Description (Type A specimen)
10	Outflow begins
25	Side face heaving and local failure
50	Local failure of front face
80	Entire peripheral region (front region) saturated
2h25	Complete failure originating in side face failure region (near end of snow layer)

Table 2 Weights of test specimens used in

	Initial (kg)	After snowmelt (kg)	Infiltration (kg)	Infiltration ratio (%)
Type A specimen	19.34	Failure	———	———
Type B specimen (1 layer of snow)	19.91	19.95	0.04	2.7
Type B specimen (2 layers of snow)	19.95	19.95	0	0

3.3.2 Cohesive soil

Two test specimens of cohesive soil were prepared, and a B test was conducted using two different slope angles: 5 degrees and 10 degrees. The purpose of this test is to see if slope angles affect meltwater outflow.

The times consumed for snow to melt showed slight differences, but the slope angle did not affect drainage; almost all meltwater flowed out of the test specimen after moving through the snow layer (Figure 15). Low permeability of the cohesive soil is thought to have affected the test results.

Figure 15 B test with different slope angles (foreground: 10 deg., background: 5 deg.)

3.3.3 Sand

A concrete form was filled with sand, and the slope angle was set to 10 degrees. Then B test was conducted (Figure 16). In this snow-on-sand test, almost all meltwater was absorbed in the sand, and drainage through the snow layer was not observed. In the next test in which the slope angle was increased to 30 degrees, no water flowed out through the snow layer even after a considerable amount of water was sprinkled over the snow layer.

These test results are thought to indicate that the inclination of the slope is not the only factor

Figure 16 Snowmelt test on sand

affecting the drainage of meltwater, and that water-absorbing capacity due to capillary action of the underlying ground is a major factor. In other words, water-absorbing or water-containing capacity due to capillary action of snow is thought to be a major factor contributing to infiltration into the underlying ground.

4. Natural snowmelt phenomena

In the laboratory tests, meltwater was observed to seep through the snow layer and eventually flow out from the lower end of the snow layer. Do similar phenomena occur in the natural world?

From the way rooftop snow melts in the real world, I have a hypothesis concerning the phenomenon of meltwater or rainwater flowing through a snow layer. In Figure 17, the lower end of the snow layer is frozen. I hypothesize that as meltwater seeps downslope through the snow layer and is refrozen at the lower end of the snow layer, the ice formed along the lower end of the snow layer becomes thicker over time. Am I wrong in assuming that if meltwater drips down from the snow layer before reaching its lower end, the phenomena mentioned above will not occur and the rooftop snow will fall to the ground sooner because meltwater will flow downslope on the rooftop surface.

Figure 17　Melting rooftop snow

An outdoor test was conducted on a lawned garden under conditions similar to the laboratory test conditions. The outdoor test revealed that meltwater infiltrated the sod from the bottom of the snow layer, but there was also considerable runoff from the lower end of the snow layer. After the test, runoff of water from an overlying snow layer on a natural slope was observed. The snow layer was about 4 m long, and the maximum snow cover thickness was about 20 cm. Four liters of black-colored water was sprinkled in the uppermost area of the snow layer to see if the water flows out from the lower end of the snow layer. As a result, black-colored water was observed to flow out from the lower end of the snow layer, as in the laboratory tests and the outdoor test conducted on the lawned ground, although the findings were not quantitative.

From the results of the observations, it can be inferred that small-scale snowmelt phenomena similar to those observed in the laboratory tests occur under the natural conditions.

5. Relationship between expressway cut-slope failure and melting of snow

Through the observation of snowmelt phenomena and laboratory testing, the cause of the slope failure in the Kuromatsunai area has been inferred:

Figure 18 shows a projection onto a topographical map of contours before the slope failure. The area of the synclinal slope on the cut-slope side is about 1500 m^2, and, as shown, the topography of the slope failure site is conducive to concentration of rainwater and meltwater in the drainage area. The Figure 19 taken at the time of the slope failure shows that the scarp is close to the lower end of the snow layer.

The drainage area is not very large but nighttime temperature had been above 4℃ for several days before the slope failure. It may be concluded that a considerable amount of meltwater had run off, in a concentrated manner, to the lower end of the snow layer continuously and steadily until infiltration into the ground in the low-lying area near the shoulder of the slope resulted in the slope failure.

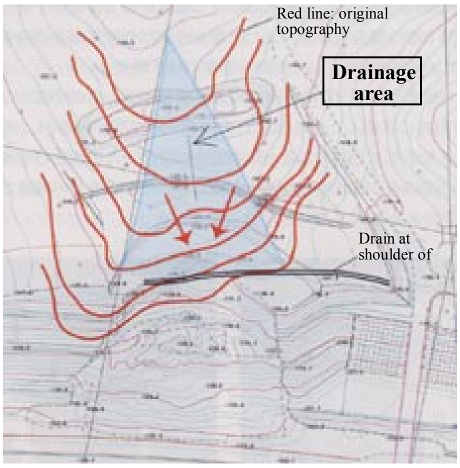

Figure 18　Slope failure site and drainage area

Figure 19　Slope failure site and drainage area

6. Good practices of slope inspection management during snowmelt

Slope inspection in early spring is important for preventing slope failure during snowmelt. It is possible, however, to inspect a slope when it is covered with snow. What are good practices?

6.1 Determining the onset of snowmelt

There is no need to worry about snowmelt-induced disaster as long as the cut slope and the upper

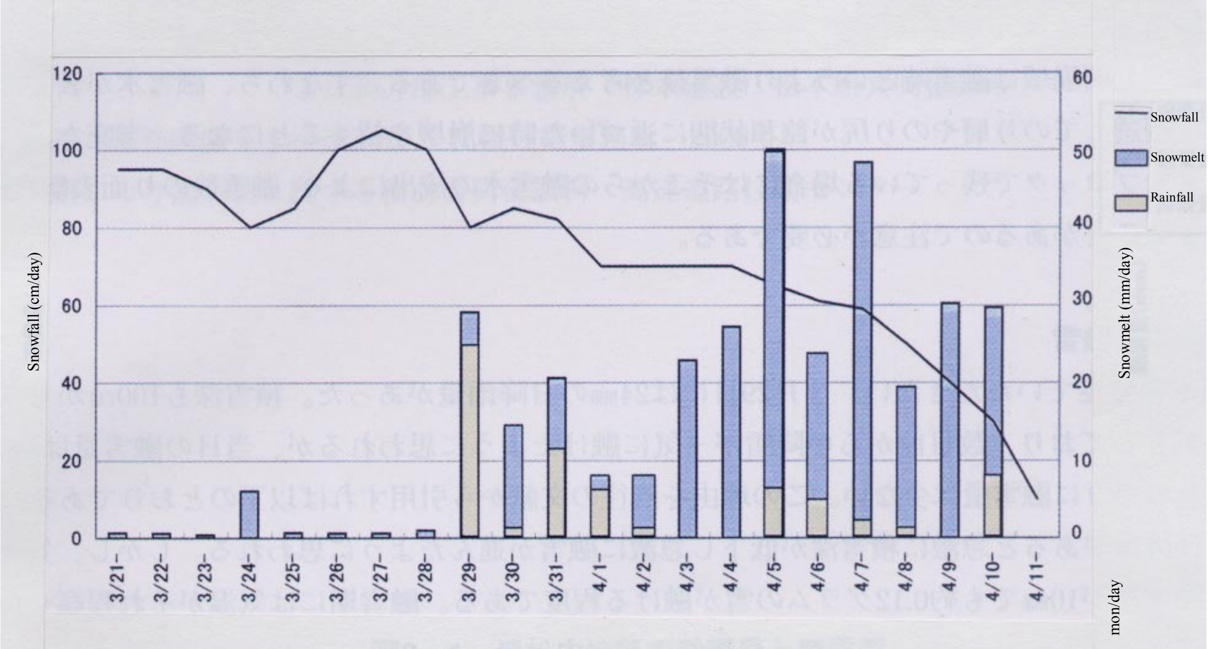

Figure 20　Snowmelt and snowfall in Kuromatsunai area

Figure 21 Snow-covered slope (April 4)

Figure 22 Snow-covered slope (April 11)

slope have sufficient snow cover. When there is sufficient snow cover, various phenomena such as granulation of snow and downslope flow of meltwater through the snow layer is likely to help minimize outflow of water from the bottom of the snow layer.

Figure 20 shows daily meltwater measurements taken with a Lysimeter at the shoulder of the slope at the Kuromatsunai slope failure site. Figures 21 and 22 show the failure site on the 4th and 11th of April. The photographed areas are not exactly the same, but these photographs enable interpretation of changes over time in snow cover conditions. On April 4, the slope was still covered with a considerable amount of snow, but the slope was beginning to be exposed at places. Judging from meltwater measurements based on Lysimeter readings, the snowmelt process was still at the first half stage. By April 11, the melting zone had reached the shoulder of the slope, and the snow layer covering the slope began to disintegrate. On the south-facing slope, large patches of slope surface began to be exposed, and meltwater flow increased. Snow cover was still visible on the upper slope. Temperatures during this period were not particularly high.

From these findings, the time at which the highest part of the cut slope begins to be exposed may be thought of as the onset of snowmelt. Since the snowmelt rate increases sharply around this time as temperatures begin to rise, meltwater flows out in a concentrated manner from the lowest part of the upper slope to the shoulder of the cut slope. At this time slope inspection management in snowy regions needs to be planned and practiced according to the site conditions.

7. Conclusion

This paper describes how snow melts and how meltwater infiltrates the ground to destabilze the cut slope through simple laboratory testing on snowmelt and observation of snowmelt processes in the natural topography.

From the results of the laboratory tests on snowmelt, the following conclusions can be drawn concerning the cut slope:

If the entire slope is covered with snow, snowmelt flows downslope through the snow layer until it flows out from the lower end of the slope. The slope, therefore, remains stable.

If the drainage system at the top of the slope is inadequate, the runoff from the lowest part of the snow layer on top of the slope may infiltrate into the slope, causing a slope failure as the snow melts.