Journal of Earth Sciences and Geotechnical Engineering, Vol.13, No.1, 2023, 11-54
ISSN: 1792-9040 (print version), 1792-9660 (online)
https://doi.org/10.47260/jesge/1312
Scientific Press International Limited

Field Observations of Water and Ice Problems in Railway Tunnels from a Maintenance Perspective

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Abstract

During the winter season, ice causes major problems in many Swedish railway tunnels. Ice, rock and shotcrete in the roof and on the walls may come loose and fall down, installations and cables can break due to ice loads and the tracks can become covered with ice. To maintain safety and prevent traffic disturbances, many tunnels require frequent maintenance. The removal of ice, loose rock and shotcrete is expensive and potentially risky work for the maintenance workers. To reduce maintenance costs, it is important to improve our knowledge of frost penetration inside tunnels and investigate the effect of ice pressure and frost shattering on load-bearing constructions. The aim of this investigation was to gather information about the problems caused by water leakage and its effect on the degradation of a rock tunnel when subjected to freezing temperatures. There are many factors that determine whether frost or ice formations will appear in tunnels. To collect information on ice formation problems, field observations were undertaken in five of Sweden's railway tunnels between autumn 2004 and summer 2005. For one of the tunnels, follow-up observations also took place in March during the years 2005, 2006 and 2007.

Keywords: Railway tunnel, field observations, ice formation, frost shattering, maintenance, degradation of rock and shotcrete, cold climate.

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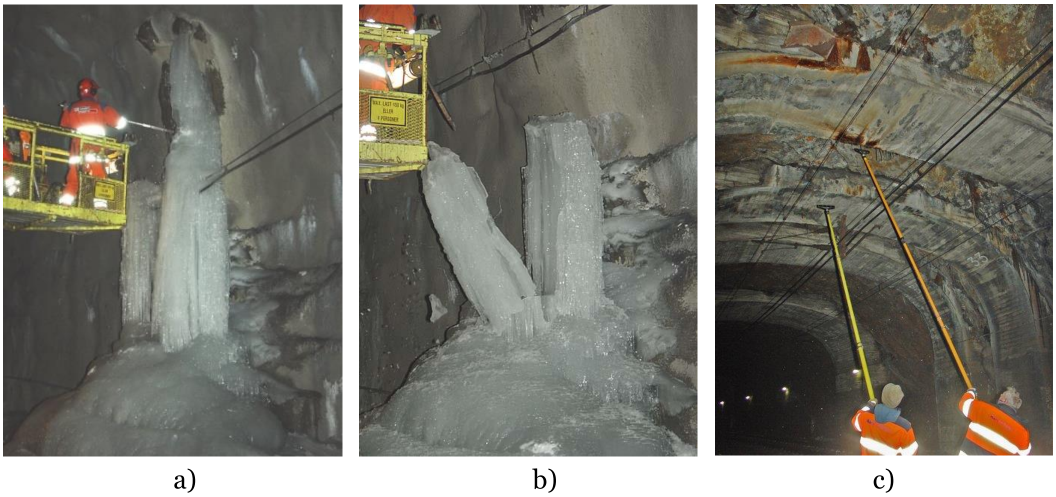
Article Info: *Received:* January 26, 2023. *Revised:* February 18, 2023.

1. Background

Ice formation in tunnels is a major problem that must be addressed frequently to ensure safe train and road traffic in the tunnels owned and operated by the Swedish Transport Administration. In railway tunnels, icicles can grow so long that they short-circuit the overhead contact line and ice formations can grow so large that they encroach on the gauge clearance and operational space of the tunnel (Figure 1). When water freezes in the rock mass and its joints, or in the interface between the rock and the reinforcing shotcrete, frost shattering can cause degradation of the rock and the shotcrete. Material can lose its load-bearing capacity and may fall down onto roads or tracks. To maintain safety and prevent traffic disruptions, many tunnels require extensive maintenance. Removal of ice, loose rock and shotcrete is both costly and risky (Figure 2). To reduce the maintenance of the tunnels, more in-depth knowledge is needed about frost penetration, the effects of ice pressure on the main load-bearing system and where in the tunnels most ice problems occur.

a) b)

Figure 1: a) Icicle in the Rönninge tunnel, 2010 (Photo: Infranord). b) Ice pillar in the Glödberget tunnel (Andrén, 2008).



a) b) c)

Figure 2: a) and b) Removal of an ice pillar in the Glödberget tunnel, 2005 (Andrén, 2008).
c) Removal of icicles from the tunnel roof above the overhead contact line using long insulating plastic rods in the Rönninge tunnel, 2005 (Andrén, 2008).

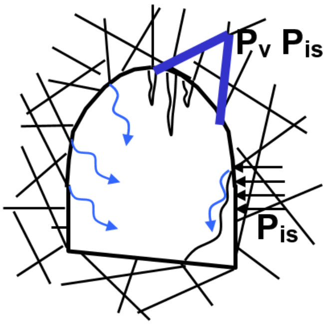
2. Problem description

2.1 Water leakage

Leakage of water occurs in all rock tunnels in some form, including moist surfaces, drips or running water. The water is led towards the tunnel via naturally occurring joints in the rock mass, but also via cracks caused by the blasting of the tunnel itself. The amount of leakage into a tunnel is affected by topography, the location of the tunnel in relation to the groundwater surface, the amount of precipitation during the year, how the water is stored in the rock and how the tunnel cuts the flow paths of the water. Furthermore, the leakage is affected by the construction of the tunnel, the quality and the execution of measures to seal the tunnel, such as grouting, reinforcement, placement of frost insulated drains and, of course, temperature conditions in the region where the tunnel is located. Today's methods for reducing or preventing problems with ice formations in tunnels, are first and foremost designed to prevent water from leaking into the tunnel by grouting, even though the main reason for grouting is to prevent a reduction of the ground water level and its impact on the environment. However, experience shows that despite extensive pre-grouting and supplementary post-grouting, it is difficult to seal the rock mass so that drips and moisture are completely eliminated. If grouting is not sufficient, the leaking water must be taken care of in some other way. Where the requirements for environmental impact are high, a waterproof construction or infiltration can be used. In other cases, the permitted amount of leaking water is disposed of by through an inner tight cladding consisting of a drainage system with insulated drain mats.

2.2 Ice formation

Water can cause problems when the leakage takes place in sections of the tunnel located in the frost zone. The magnitude of the ice problems is dependent on the freezing rate (e.g., Matsuoka, 2001 or Walder and Hallet, 1985), changes in the freezing periods and their duration (French, 1996). If a freezing period has a long duration, or if the freezing rate is rapid, the leaks become frozen. The water freezes and ice formations are created, which act like a plug for the leakage point; it 'freezes dry'. If instead the leak is subjected to short periods of freezing and thawing, the joint will never become frozen and water will continue to leak, resulting in growing ice formations. Another factor in ice growth is that the leakage water transfers heat from inside the rock mass to the cold tunnel wall. The heat content of the water prevents the rock from freezing despite the freezing tunnel air temperatures. As a result the leak will continue causing ice formations to grow where the water meets the cold tunnel air. Ice developing in joints and cracks can exert a pressure on the joint or crack surface (P_{is}), which leads to frost shattering of rock and shotcrete (Figure 3).



P_v = Pressure from water
P_{is} = Pressure from ice

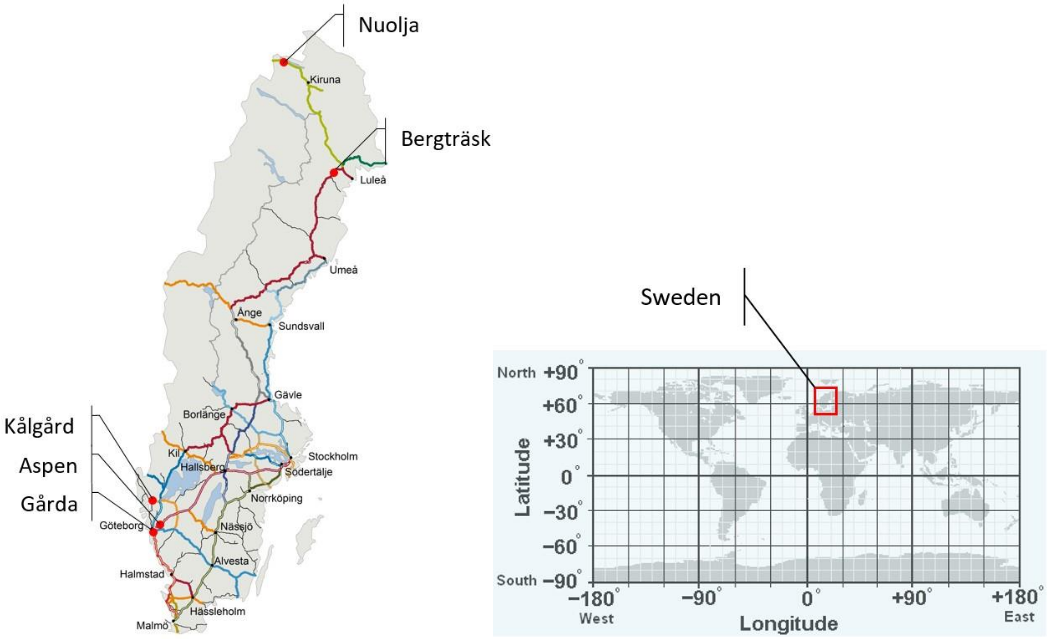
Figure 3: Ice loads (P_{is}) arising when leakage occurs in the frost zone (Andrén, 2004).

2.3 Frost penetration

In 1999, the Swedish Rail Administration (now the Swedish Transport Administration) initiated a research project called 'Frost penetration in railway tunnels'. The purpose of the project was to find a practical and simple method for identifying the tunnel sections where the air temperature is permanently below freezing. Frost penetration increases in a tunnel when the tunnel air is set in motion by: i) thermally induced air flows; ii) trains that run through the tunnel; and iii) wind that creates a pressure difference between the tunnel entrances. Sandberg et al. (2002), showed that the dominant cause of frost penetration in most tunnels is the constant thermally induced air flow. In short tunnels, where the height difference between the tunnel entrances is relatively small, the wind generates the dominant air flow through the tunnel. Here, the entire tunnel can be exposed to the same temperature conditions as outside the tunnel. Air flows due to train traffic have been proven to have little effect on frost penetration. To determine the expected temperature conditions along a tunnel, the Swedish Transport Administration performed long-term field measurements of temperatures in railway tunnels. The measurements showed that the frost penetrates further into the tunnels than previously expected. In many cases, frost penetration occurs throughout the whole tunnel, even in tunnels of over 1000 m in length (Andrén, 2008-2016 and Andrén et al., 2020b).

2.4 Fall-outs of rock and shotcrete

During the early 2000s, the Swedish Railway Administration noticed an increase in reported fall-outs of rock and shotcrete in the railway tunnels. To name a few, rock fall-outs were reported in the Bergträsk, Aspen and Kålgård tunnels and shotcrete fall-outs were reported in the Gårda, Nuolja and Bergträsk tunnels (Figure 4).



a) b)

Figure 4: a) Tunnels with reported fall-outs of rock and shotcrete in the early 2000s (Andrén et al., 2020a).
b) World map with latitude and longitude.

In several of the reported fall-outs, water and ice were suspected to be the cause of the damage. For example, there were ice layers on the shotcrete falls and at the exposed rock surface where the shotcrete had been attached. This began a number of research projects managed by the Swedish Transport Administration. One project that consisted of field observations is presented in this article. During these field observations, several cases of rock and shotcrete fall-outs were observed. They often occurred in wet areas, i.e., in tunnel sections with groundwater leakage problems. The reason could be that access to water during freezing temperatures deteriorates the rock, the shotcrete and the shotcrete-rock interface due to frost shattering and consequently reduces the load-bearing capacity of the tunnel (Figure 3). A licentiate work was initiated which, with the help of laboratory freeze-thaw experiments on saturated shotcrete-rock samples, showed the degradation of rock and shotcrete and explored how adhesion is affected by frost shattering. The licentiate work revealed that freezing temperatures, and hence ice growth, caused more damage to the shotcrete-rock samples that had access to water during freezing than those samples that did not have access to water (Andrén, 2009 and Andrén et al., 2020a).

3. Field observations

3.1 Survey

The Swedish Transport Administration wanted to find out where in the tunnels and when the problems with ice formations arose and where preventative measures should be taken to get the most benefit from the maintenance work. Field observations were undertaken in five of Sweden's railway tunnels between autumn 2004 and summer 2005 (Andrén, 2008).

3.1.1 Selection of tunnels

In order to select suitable tunnels for the field survey, information was collected from each region through interviews with regional rock technicians, track managers and maintenance managers. The criteria for selecting a tunnel were that it had problems with ice, these problems should be relatively well documented, that it should be close to one of the Swedish Meteorological and Hydrological Institutes (SMHI) climate stations and be relatively easily accessible for inspection (enough time to access the tracks and proximity to driveable roads). The selected tunnels were the Nuolja tunnel, the Laduberg tunnel and the Glödberget tunnel in the north of Sweden, while in the Stockholm area the Rönninge and the Kvedesta tunnels were selected (Figure 5). General data were collected from each tunnel, for example, design, climatic conditions, information on rocks and hydrology, etc. During the inspections, an assessment was made of leakage, moisture and ice presence in the tunnels. The inspection was performed visually from ground level. It was of great importance that the data collection was uniform. In order to ensure the same basis for assessment, all inspections were carried out by one and the same person - Anna Andrén.

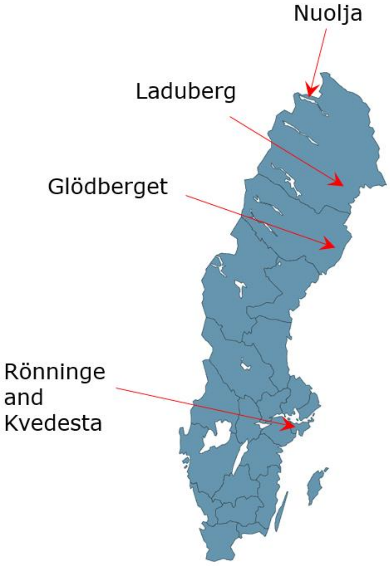


Figure 5: Location of selected tunnels.

3.1.2 Timing of inspections

The selected tunnels were inspected on four different occasions in the north and three occasions in the Stockholm area, in order to examine the variation in the problems throughout a full year and to determine the effect and impact of the seasonal climate cycle. The first inspection was in the autumn while water was still leaking into the tunnels. The second inspection was at the beginning of the freezing period, when the leakage points began to freeze and ice formations were formed. The third inspection was performed during the winter, when the tunnels had been frozen for a while, in order to tell whether any leaks were active and to examine how the ice formations had developed. The fourth inspection was in the spring, when the tunnels had begun to thaw and the leaks were active again. In the Glödberget tunnel, inspections were carried out in March during three consecutive years with the intention of recording the variations from year to year.

3.2 Explanation of documentation

The observations made at the inspections have been transferred to bar charts. The height of the bar refers to the number of drip observations (yellow bars) or ice observations (blue bars) over a distance of 100 m (Figure 6). The 100 m distance starts 100 m before the specified section in the chart and extends to and includes the specified section. At the end of each tunnel, the section may not be exactly 100 m. If so, the length is indicated in the chart, see the last bar in Figure 6.

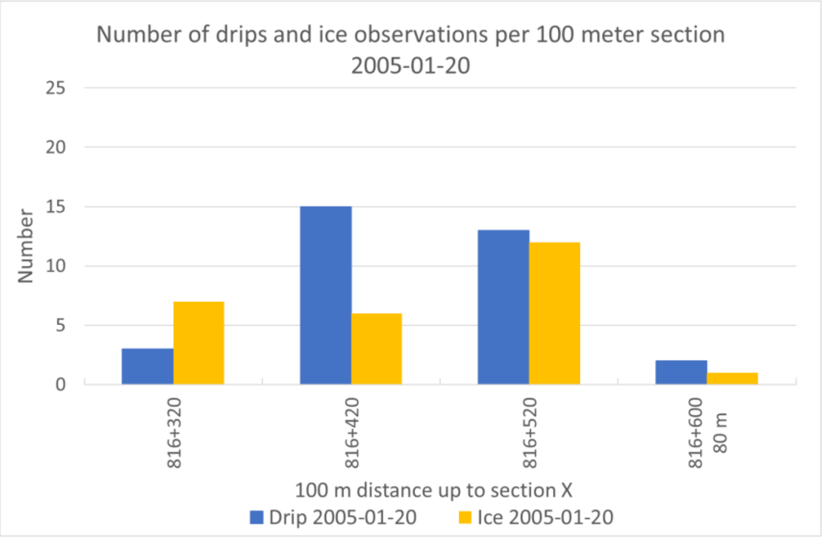


Figure 6: Explanation of the bar charts.

The location of different observations along the tunnels are given in accordance with the Swedish Transport Administrations chainage system. The term ‘chainage km 20+100’ means that the measuring length is 20 km and 100 m from a specified zero point. The zero point for all the tunnels is Stockholm. The term ‘ice observations’ refers to icicles, ice pillars or ice layers on ballast. If an icicle in the roof and ice layers on the ballast surface originate from the same the leak, it is only recorded as one ice observation in the charts. The same applies to drip observations, i.e., if one leak gives rise to a number of drips. Diagrams of daily average values for temperature and precipitation are displayed to illustrate what weather conditions the tunnel had been exposed to before each inspection. Photos of the same sections were taken during the inspections to allow for a comparison between the different occasions when inspections were carried out and to identify variations over the year. Attempts have been made to interpret differences and similarities among the tunnels.

3.3 Results for the Nuolja tunnel

3.3.1 Facts about Nuolja

The Nuolja tunnel is located in the northernmost part of Sweden (Figure 5). The tunnel was built in the late 1980s and came into operation in 1990. It is a single-track tunnel with a total length of 1430 m, of which 1160 m consists of a rock tunnel and the remaining 270 m of concrete tunnel close to the entrances. The tunnel has a width of 7.0 m and a height of 7.0 m above the top of the rail, with an inclination to the north of about 9 ‰. The rock mass consists of phyllite with a flat structure and the soil layers above the rock are thin and consist of silty sandy moraine.

3.3.2 Actions carried out in the Nuolja tunnel

Before 1990, the Malmbanan went through an older tunnel that came into operation as early as 1902. A new tunnel was built because there had been major problems with ice formations in the older tunnel. However, problems with leakage and ice also arose in the new tunnel. The Swedish Rail Administration tried to reduce the problems by grouting the rock mass with polyurethane-based grout in 1992. During 1992-1993, attempts were also made to drain the surrounding rock mass by installing electrically heated drainage pipes in certain parts of the tunnel walls (Figure 7). The problems with ice continued and, in 1996, selected sections were also frost insulated with polyethylene mats covered with shotcrete. Furthermore, concrete elements with insulating rock wool were installed. Despite these measures, many problems remain and the tunnel requires many hours of maintenance during the winter months to address the problems with icicles and ice formation.

Figure 7: Drainage pipe at chainage km 1512+610, Nuolja 2004-10-07 (Andrén, 2008).

3.3.3 Climate data for Nuolja

Temperature information was taken from the Swedish Transportation Administration's weather data station No. 2517 Tornehamn and precipitation information from SMHI's climate station at Abisko. Figure 8 shows the daily values for precipitation and average temperature for the winter period 2004-2005.

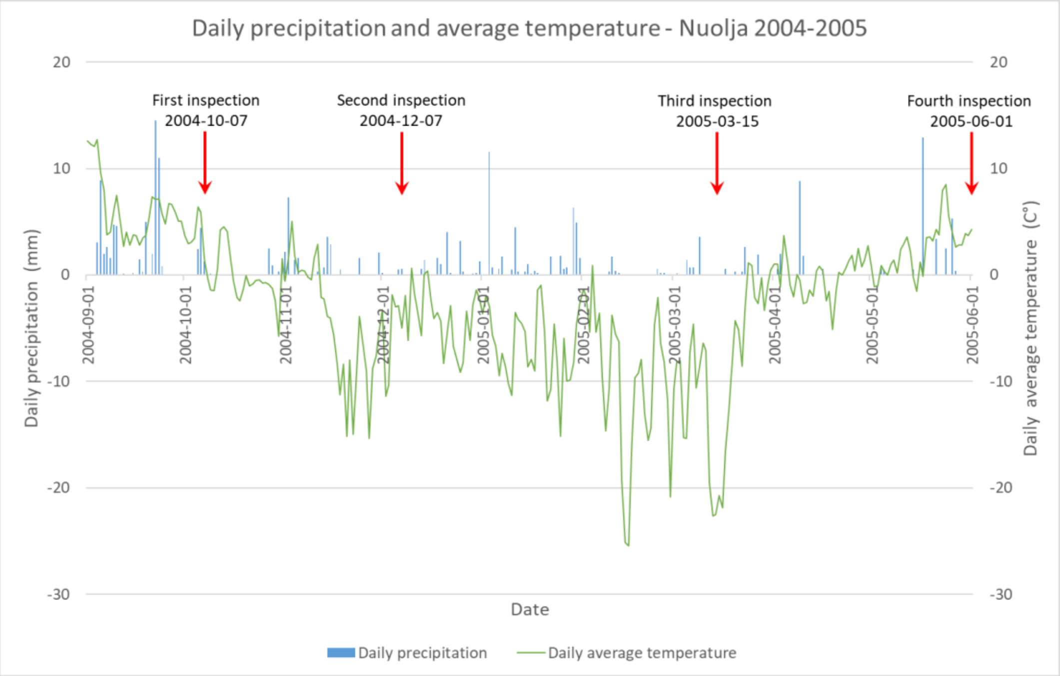


Figure 8: Daily average for precipitation and temperature.

3.3.4 Results of the inspections in the Nuolja tunnel

In the first inspection on 7 October 2004, the tunnel was very wet. The temperature had been above freezing and there had been a lot of precipitation in the area the month before the inspection (Figure 8). There were many damp and wet areas in the roof and on the walls of the tunnel. Drips from the roof and walls occurred along the entire tunnel, with an increased concentration between chainage km 1512+300 to 420 (red ellipse in Figure 9a). The green ellipse in Figure 9a shows an area that had only a slight leakage of water in the first inspection. In the second inspection, many ice observations were made (compare the green ellipses in Figure 9a and b).

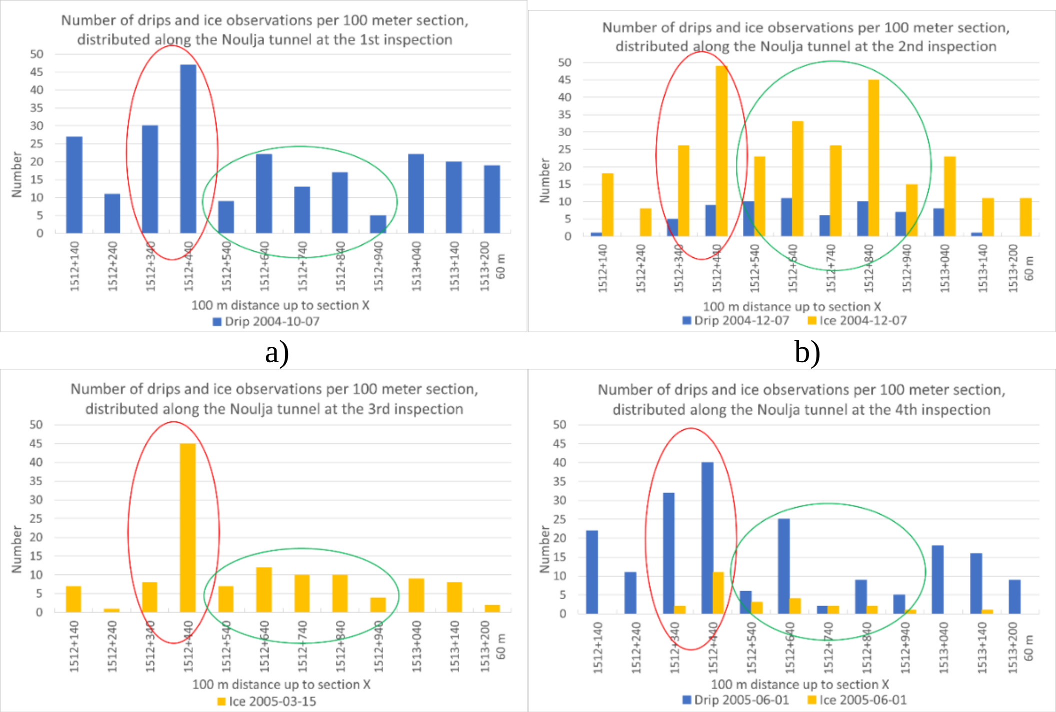
In the second inspection on 7 December 2004, the temperature had been just below freezing (Figure 8). The freezing rate had been slow, which had caused the leakage to continue at the same time as the temperature had been low enough for ice to form. Many icicles and ice layers were observed, and large ice pillars had formed at the leakage points in the walls (Figure 10).

Most observations were made at the same location as in the first inspection, between chainage km 1512+300 to 420 (red ellipse in Figure 9b), but also between chainage km 1512+500 to 900, which had an increased concentration of ice formations. These ice formations had been formed despite the fact that, in the first inspection, there were not so many drip observations or as much moisture in this area (compare the green ellipses in Figure 9b and a). Some leakage from the roof and walls remained in the inner parts of the tunnel, despite the cold temperature outside the tunnel. According to the maintenance worker present, the beginning of the winter had been unusually mild and problems with icicles and ice layers had been relatively minor.

The most severe problems often occur at the entrances, where many icicles grow when the cold period starts around the beginning of November. These problems decrease when the leakage points at the entrances ’freeze dry’. Compare the numbers of ice observations in the outer parts of the tunnel to the inner parts during the inspection in December (Figure 9b).

In the third inspection on 15 March 2005, the temperature had been below freezing for a long time (Figure 8). All drips had stopped and there were no moist surfaces along the tunnel. The concentration of ice formations between chainage km 1512+300 to 420 was similar to that in the previous inspection (red ellipse in Figure 9c). Ice formations had grown in several sections and become more extensive (Figure 12). In total, the number of ice observations had decreased from the second inspection, especially the concentration between chainage km 1512+500 to 900 (compare green ellipse in Figure 9c and b). Since the second inspection, ice had been removed during maintenance work and no new ice growth had taken place during that time.

In the fourth inspection on 1 June 2005, the temperature had been above freezing for a long time (Figure 8). There were still a few ice formations that had not yet melted. The tunnel was once again exposed to many drips, as well as moist areas on the walls and roof. The concentration of drips was again between chainage km 1512+300 to 440 (red ellipse in Figure 9d). Between chainage km 1512+500 to 900 (green ellipse in Figure 9d) only a few areas of dripping water were observed.



a) b)

c) d)

Figure 9: Number of drips and ice observations per 100 m section for the Nuolja tunnel, 2004/2005.

3.3.5 Photos from the inspections

Many icicles and ice layers were observed during the second inspections and large ice pillars had formed at the location of the leakage points on the walls (Figure 10).

Figure 10: Ice pillar, Nuolja chainage km 1512+284 right, 2004-12-07 (Andrén, 2008).

In the first inspection, it was observed that the shotcrete in the roof to the left of the track at chainage km 1512+210 had separated from the rock and fallen down on the ballast surface. The rock was exposed, and water leaked from the exposed rock surface (Figure 11).

Figure 11: Fall out of shotcrete in roof, Nuolja chainage km 1512+210 roof on the left side, 2004-10-06 (Andrén, 2008).

Figure 12 shows ice around one of the drainage pipes in the rock mass. These drainage pipes were initially heated by electricity and the idea was that the pipes would lead the leakage water down to drainage pipes on the tunnel floor. That worked relatively well until the heating system failed. The drainage pipes in the rock mass still carry a large amount of water into the tunnel but, instead of flowing in a heated drainage pipe, the water flows along the outside of the pipes and gradually freezes as it meets the cold tunnel air, which creates growing ice pillars.

Figure 12: Drainage pipe, Nuolja chainage km 1512+610 left, at different inspections (Andrén, 2008).

Another problem was leakage where the rock and the concrete arches are connected. At chainage km 1512+626, there was a leak that during the winter inspections had formed a large ice pillar (Figure 13). At the time of the inspection in December, the leak was still active.

Figure 13: Water leakage where the rock and the concrete arches are connected. Nuolja chainage km 1512+626 (Andrén, 2008).

3.3.6 Discussion

Although the tunnel is relatively long (1430 m), many ice formations were observed in the inner parts of the tunnel. The number of ice observations near the entrances were not that many in comparison to the number of drip observations in the same areas, see chainage km 1512+120 to 240 and 1513+140 to 200 in Figure 9. In contrast, in the inner parts of the tunnel, there were a greater number of ice observations in comparison to the number of drip observations. This was observed, for example, at chainage km 1512+540 to 940 in Figure 9 (green ellipse). Consequently, more ice is formed from drips in the inner parts of the tunnel than from the drips at the entrances. The drips that are closer to the tunnel entrances freeze at a faster rate. The entire rock mass freezes and the leakage ’freezes dry’, i.e., ice forms in the water-bearing joints, consequently these paths freeze and prevent further water leakage. The drips in the inner parts of the tunnel are not exposed to the same cool temperatures because the rock mass itself contains stored heat energy that constantly heats up the cold outside air that penetrates into the tunnel. Therefore, the rock mass remains unfrozen here. As a result, the path of the leak remains open and can continue to carry water to the tunnel walls and roof causing ice to form when the water reaches the cold tunnel air.

3.4 Results for the Laduberg tunnel

3.4.1 Facts about Laduberg

The Laduberg tunnel is located near Älvsbyn in the north of Sweden (Figure 5). The tunnel was built in the late 1970s and came into operation in 1982. It is a single-track tunnel with a total length of 996 m, of which 976 m consists of a rock tunnel and the remaining 20 m of concrete tunnels in the tunnel entrances. The tunnel has a width of 7.0 m, a height of 7.0 m above the top of the rail and an inclination of 2 ‰ to the north. The rock mass consists of grey to red medium-coarse-grained granite with elements of pegmatite. There are isolated zones with foliated schistose rock. The rock cover is about 30 m, with a maximum value of 43 m and a minimum value of 3 m. The soil layer above the rock is between 1-15 m and consists of block-rich silty moraine.

3.4.2 Actions carried out in the Laduberg tunnel

The Laduberg tunnel has major problems with ice formation and frost shattering every year. When the tunnel was built, no systematic pre-grouting was done and, as problems occurred, post-grouting and the installation of drains have been carried out with varying results. For example, about 1500 m^2 of drains were installed in 1992. Some were equipped with heating cables to thaw potential ice formations. These heating cables do not work today. Instead, frost insulated drain mats made of polyethylene have been installed to lead the water down to the drainage system on the tunnel floor. However, problems with ice formations behind the drains have led to frost shattering. These problems can occur when the edges of the drains have not been sufficiently sealed or when the drains do not extend all the way down to the tunnel floor. Scaling of the roof and walls is performed annually and reinforcement with fully grouted rock bolts has been carried out as needed. In addition to the rock bolts, larger concrete arches have been constructed in four places to support the tunnel roof and walls (Figure 16b). Prior to an inspection of the rock surface in the early 2000s, several of the drains were removed to be replaced with new drains. In some sections, no new drains were installed because the rock surfaces were dry. The sections are still dry after several years and this indicates that the paths of the leaks have changed or that they may have been sealed naturally. In 2003, the Swedish Rail Administration tried to reduce problems with ice layers on the track by installing heating cables in the ballast bed along the entire tunnel. The cable was laid at a depth of about 30 cm into the ballast and placed some distance from the tunnel wall. The idea was to keep the ballast unfrozen, so that leakage water could flow along the wall, down into the ballast and further down to the drainage system along the tunnel floor. This prevents the leakage water from freezing in the cooled ballast and forming ice layers that spread over the tracks. During the following winter seasons, the heating cables have worked well, and ice layers have not occurred to the same extent as in previous years.

3.4.3 Climate data for Laduberg

Temperature information was taken from the Swedish Transportation Administration's weather data station No. 2539 Klöverträsk and precipitation information from SMHI's climate station at Älvsbyn. Figure 14 shows the daily values for precipitation and average temperatures for the winter period 2004-2005.

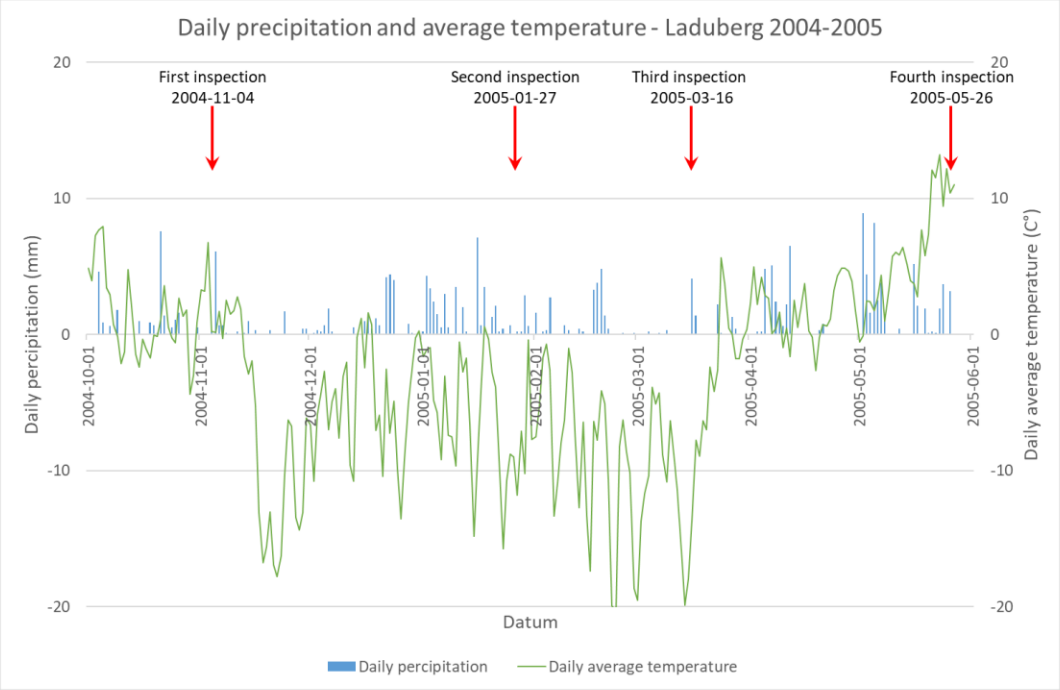


Figure 14: Daily average for precipitation and temperature.

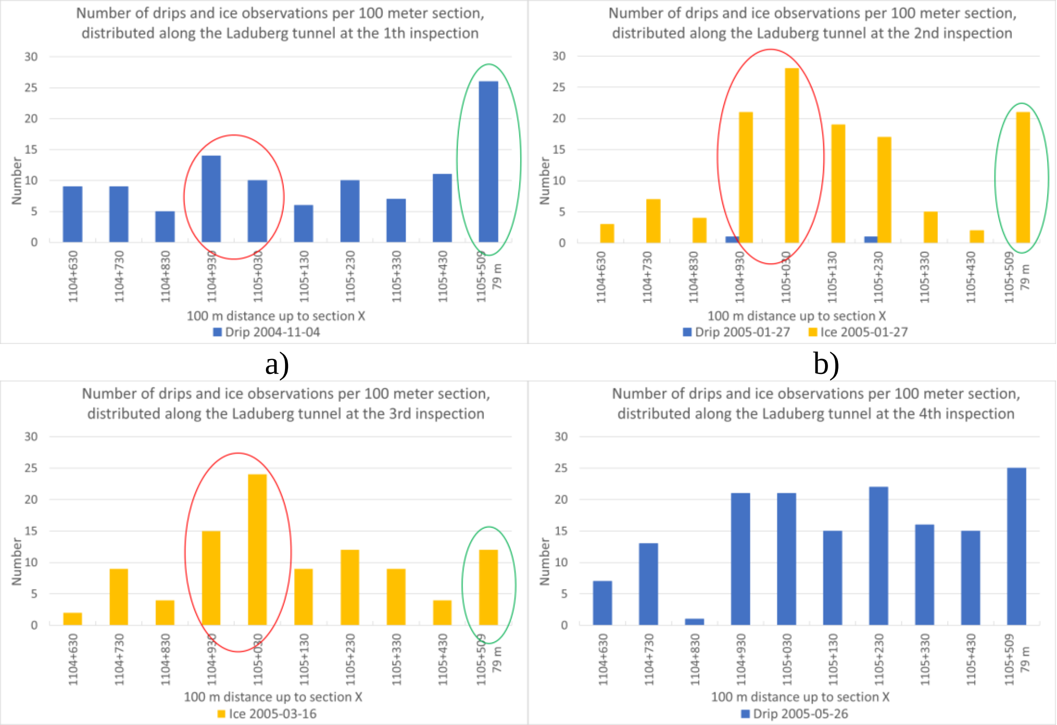
3.4.4 Results of the inspections in the Laduberg tunnel

In the first inspection on 4 November 2004, the tunnel was very wet. When considering the occurrence of wet sections, the amount of precipitation should be taken into account. In August and September, heavy rainfall occurred in Älvsbyn, while the precipitation in October was limited (Figure 14). Depending on the storage capacity of the rock mass and the soil above, it might take some time before the rainfall reaches the tunnel. Drips occurred throughout the tunnel with an increased concentration around chainage km 1104+870 to km 1105+030 and chainage km 1105+450 to 509 (red and green ellipse respectively in Figure 15a). In the latter area, it was mainly drips from the roof.

In the second inspection on 17 January 2005, the outside temperature had been negative for a long time, but the temperature had fluctuated between -20°C and +3°C. The tunnel was relatively dry but a few leaks in the inner part of the tunnel were still active. The temperature changes might have caused many ice formations in the tunnel (Figure 14). Icicles, ice pillars and ice layers occurred in large parts of the tunnel. Most ice observations were made in the inner parts of the tunnel at chainage km 1104+870 to km 1105+030 (red ellipse in Figure 15b). A large number of ice observations were also made between chainage km 1105+450 to 509 (green ellipse in Figure 15b).

In the third inspection on 16 March 2005, the temperature had been between -5 to -25°C for a long time (Figure 14). All the drips had stopped and there were no damp or wet surfaces along the tunnel. The ice formations were found in almost all the same places as during the second inspection, but slightly fewer in number and even smaller in volume (compare green ellipses in Figure 15c and b).

In the fourth inspection on 26 May 2005, the temperature had been positive for a long time (Figure 14). All the ice had melted, and the tunnel walls were again very wet. There were some drips from the roof, but otherwise the roof was relatively dry. The number of drip observations had increased in almost every section along the tunnel compared to the first inspection (compare Figure 15d and a).



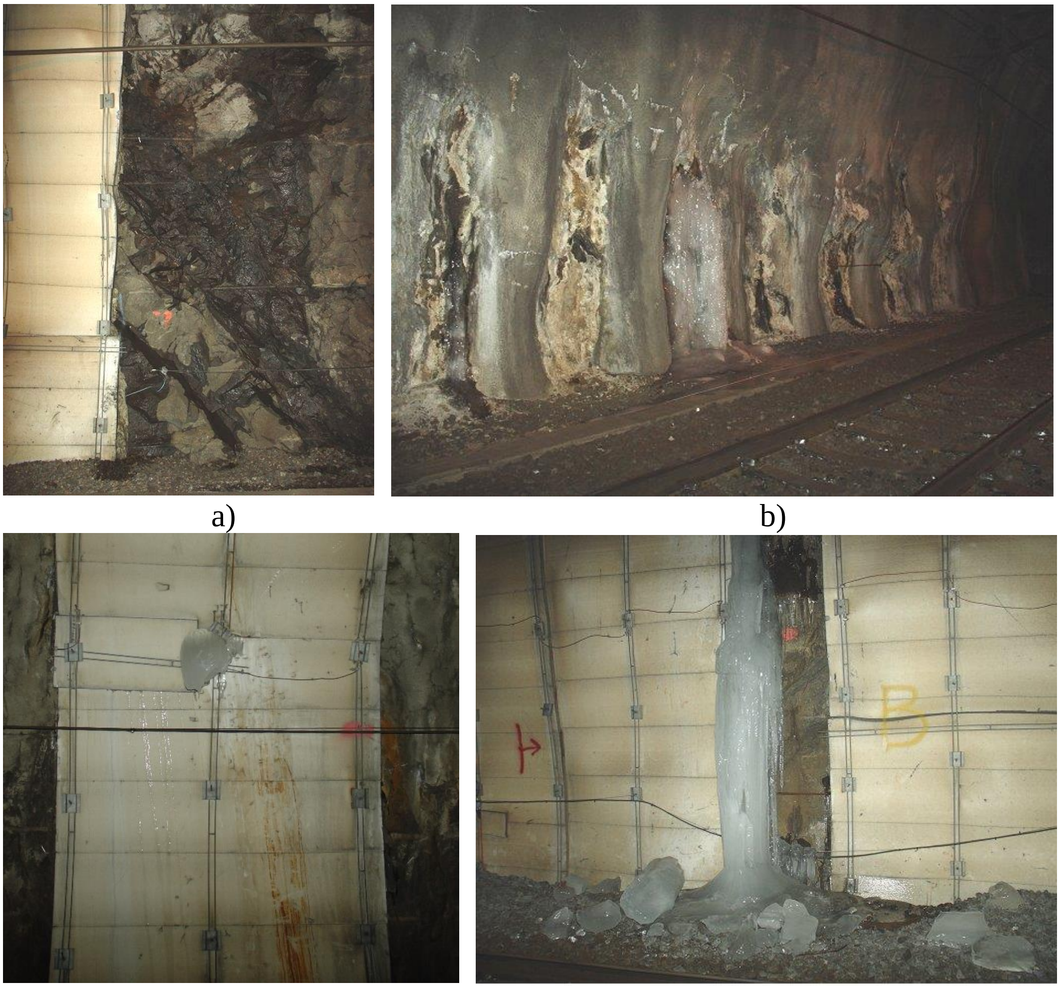
a) b)

c) d)

Figure 15: Number of drips and ice observations per 100 m section for the Laduberg tunnel, 2004-2005.

3.4.5 Photos from the inspections

In the Laduberg tunnel, only the roof is sprayed with shotcrete and the rock walls are only reinforced with rock bolts where required. The drain mats are not covered with shotcrete. Many leaks in the tunnel are connected to the drains. In Figure 16a, the water leakage follows the fracture plane in the rock, which makes it difficult to seal the drain against the rock and get the water to stay inside the edge of the drain. Figure 16b shows water leakage and ice formation in an area that is reinforced with shotcrete arches. In Figure 16c, the leakage appears in the joint between two drain mats. An icicle has formed in the centre and a large area was wet. In Figure 16d, a large ice pillar has formed next to a drain, due to a gap between two separate drains. The ice pillar could have been avoided by extending the drain width and connecting the two drains.



a) b)

c) d)

**Figure 16:a) Leakage that spreads in the fracture plane next to the drain, Laduberg chainage km 1104+675 left, 2004-11-04 (Andrén, 2008).
b) Water leakage and ice formations at shotcrete arches in Laduberg chainage km 1105+185 left, 2005-01-27 (Andrén, 2008).
c) Water leakage through drains resulting in ice formations, Laduberg chainage km 1104+911 right, 2005-01-27 (Andrén, 2008).
d) Ice pillar between two drains, Laduberg chainage km 1104+932 right, 2005-01-27 (Andrén, 2008).**

3.4.6 Discussion

The current winter period was unusually mild and, therefore, the problems with icicles and ice layers had been relatively small in number according to the maintenance workers. There were only about 3-4 places where special efforts had been needed, in the form of heating elements. The biggest problems arose in the tunnel entrances where many icicles grew until the beginning of November, when the cold season started. These problems subsided when the leakage points in the entrances froze. The inspections showed that in almost all sections along the tunnel, the number of drips was higher during the fourth inspection in the spring than during the first inspection in the autumn (compare Figure 15d and a). This variation in the number of drip observations over the year should be kept in mind when performing drip mapping for the assessment of drainage needs. The ratio between the proportion of drips and the number of ice formations is similar to that in the Nuolja tunnel. The number of drips at the beginning and end of the tunnel results in less ice than the amount of ice that occurs from drips in the middle of the tunnel.

3.5 Results for the Glödberget tunnel

3.5.1 Facts about Glödberget

The railway tunnel through Glödberget is located south of Umeå in the north of Sweden (Figure 5). The tunnel was built in 1994-1995 and came into operation in October 1995. It is a single-track tunnel with a total length of 1680 m, of which 1350 m consists of rock tunnels and the remaining 330 m of concrete tunnel (60 m in the south and 270 m in the north). The track tunnel is 8.0 m wide and the height above the top of the rail is 7.3 m. Running parallel to the track tunnel is a 610 m long service tunnel that has three entrances connecting it with the track tunnel. The tunnel has an inclination of 12.5 ‰ and decline to the north. The bedrock in Glödberget consists mainly of weathered grey, medium- to coarse-grained granite. The granite has small pieces of pegmatite and sedimentary gneiss with a low cracking frequency. The rock mass consist of large blocks with fracture systems of steep and horizontal joints. According to the rock classification, the rock quality is for the most part good to very good. The rock cover is about 30-50 m, and the overlying layers of moraine are thin.

3.5.2 Actions carried out in the Glödberget tunnel

When the Glödberget tunnel was built, systematic pre-grouting was carried out and in some parts drains were also installed to divert the water that could not be prevented from leaking into the tunnel by the grouting. Complementary drains were installed in 1995, 1996 and 1997. However, the problems remained and in 1998 approximately 1600 m^2 of drains were installed, consisting of PE mats with fibre-reinforced shotcrete. Despite the fact that such a large portion of the rock surface is covered with drains, the problems with ice in the tunnel remain.

3.5.3 Climate data for Glödberget

Temperature information was taken from the Swedish Transportation Administration’s weather data station No. 2442 Bjurholm and precipitation information from SMHI's climate station at Röbäcksdalen. Figure 17 shows the daily values for precipitation and average temperature for the winter period 2004-2005.

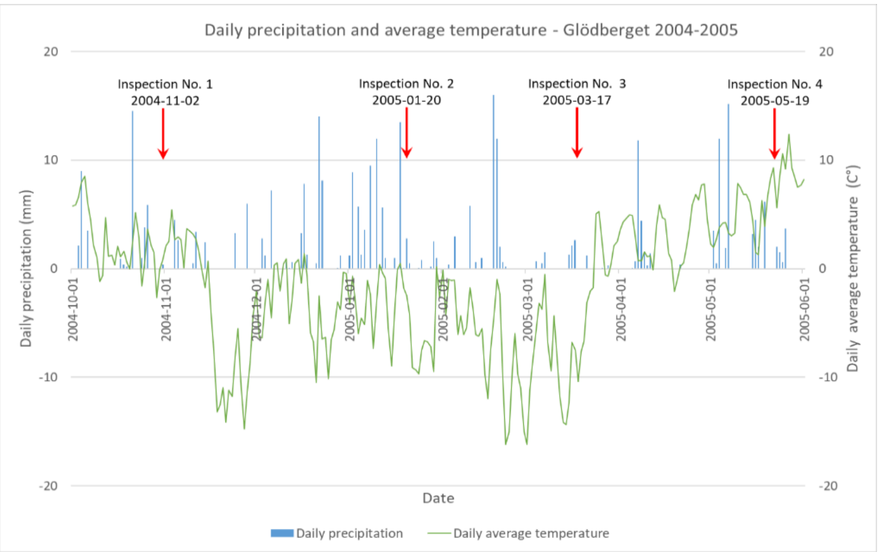


Figure 17: Daily average for precipitation and temperature.

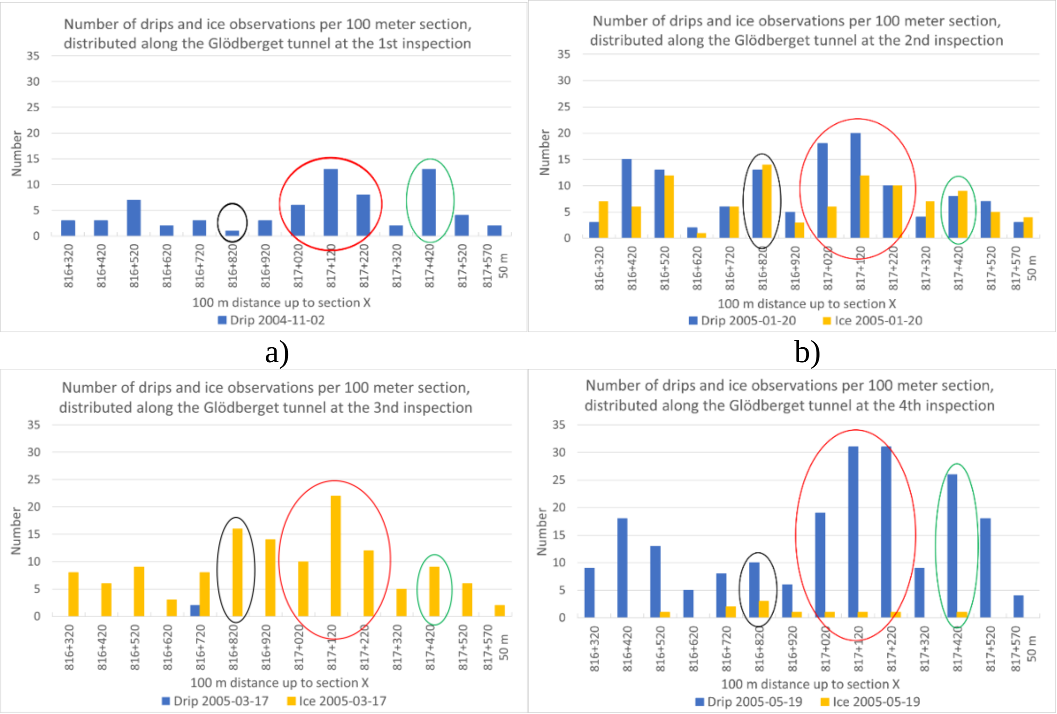
3.5.4 Results of the inspections in the Glödberget tunnel

Prior to the first inspection, the temperature had been below freezing on only a few occasions (Figure 17). The first inspection was carried out on 2 November 2004. A large part of the tunnel walls and roof were moist. The distribution of drips was more even throughout the Glödberget tunnel than the two previously described tunnels, but between chainage km 817+020 to 220 and between chainage km 817+420 there were more drips than in other parts of the tunnel (see red and green respectively ellipse in Figure 18a). The black ellipse in Figure 18a (between chainage km 816+760) marks an area where there were no major drips in the first inspection. In the following inspection, on 20 January 2005, ice formations were observed at this location, despite the lack of drips in the first inspection (Figure 18b and c).

Before the second inspection on 20 January 2005, the outside temperature fluctuated around 0°C (Figure 17). Therefore, the leakage points in the tunnel remained unfrozen, but the temperature inside the tunnel was cold enough for ice to form. Many drips were observed in the tunnel, mainly from the roof and from the left shoulder. The dripping water had resulted in large ice pillars and large ice layers on the ballast and tracks. The same sections marked with red and green ellipses in Figure 18b were still relatively moist and a large number of ice formations were observed (Figure 18b). The larger areas that were relatively dry in the first inspection were still dry and free from ice observations. An exception was the section marked with the black ellipse in Figure 18b. Here the roof was dry and the wall was damp in the first inspection but, at the second inspection, the wall was wet and several ice pillars had formed. There was even a leak from the roof with icicles forming as a result.

Between the second and third inspection, the temperature had remained below freezing (Figure 17), which led to the tunnel being almost completely frozen during the third inspection on 17 March 2005. The surface of the tunnel was dry and only one leak was still active, a known problem at chainage km 816+665. A large ice pillar was applying load to a cable in the left shoulder (Figure 21, date 2005-03-17). Incidentally, there were many large ice pillars along the walls and large areas of ice layers on the ballast and tracks. Ice formations were found in approximately the same places as in the second inspection (Figure 18c). In the section around the black ellipse, many ice formations had formed, while at the green ellipse, fewer ice formations had formed than might have been expected taking into account the number of drip observations in the first inspection (compare Figure 18a and c).

After the third inspection, the temperature was above freezing almost all the time until the fourth inspection on 19 May 2005 (Figure 17). In that inspection, the tunnel had thawed and was very moist. A few ice formations were observed in the tunnel. These examples were from sections where the ice pillars had been very large and had not had time to melt down. Otherwise, the ice had melted away and the tunnel was very moist. The number of drip observations had increased significantly compared to the first inspection, see especially the red and green ellipses in Figure 18a and d. In the section around the black ellipse, the wall was completely wet and there were drips of water from the roof. This was completely different from the conditions observed in the first inspection as, at that time, that section did not have much moisture or many drips.



a) b)

c) d)

Figure 18: Number of drips and ice observations per 100 m section for the Glödberget tunnel, 2004/2005.

3.5.5 Photos from the inspections

A problem observed in several places was broken handrails (Figure 19a and b). These problems often occurred near the locations of leakage points. The damage to the handrail was probably caused by the formation of large ice pillars during the winter, which broke the brackets holding the handrail to the wall and the handrail itself. Another problem observed was cracked shotcrete along the walls and roof (Figure 19b). Many cracks were calcareous, but moisture and drips penetrated through several cracks.

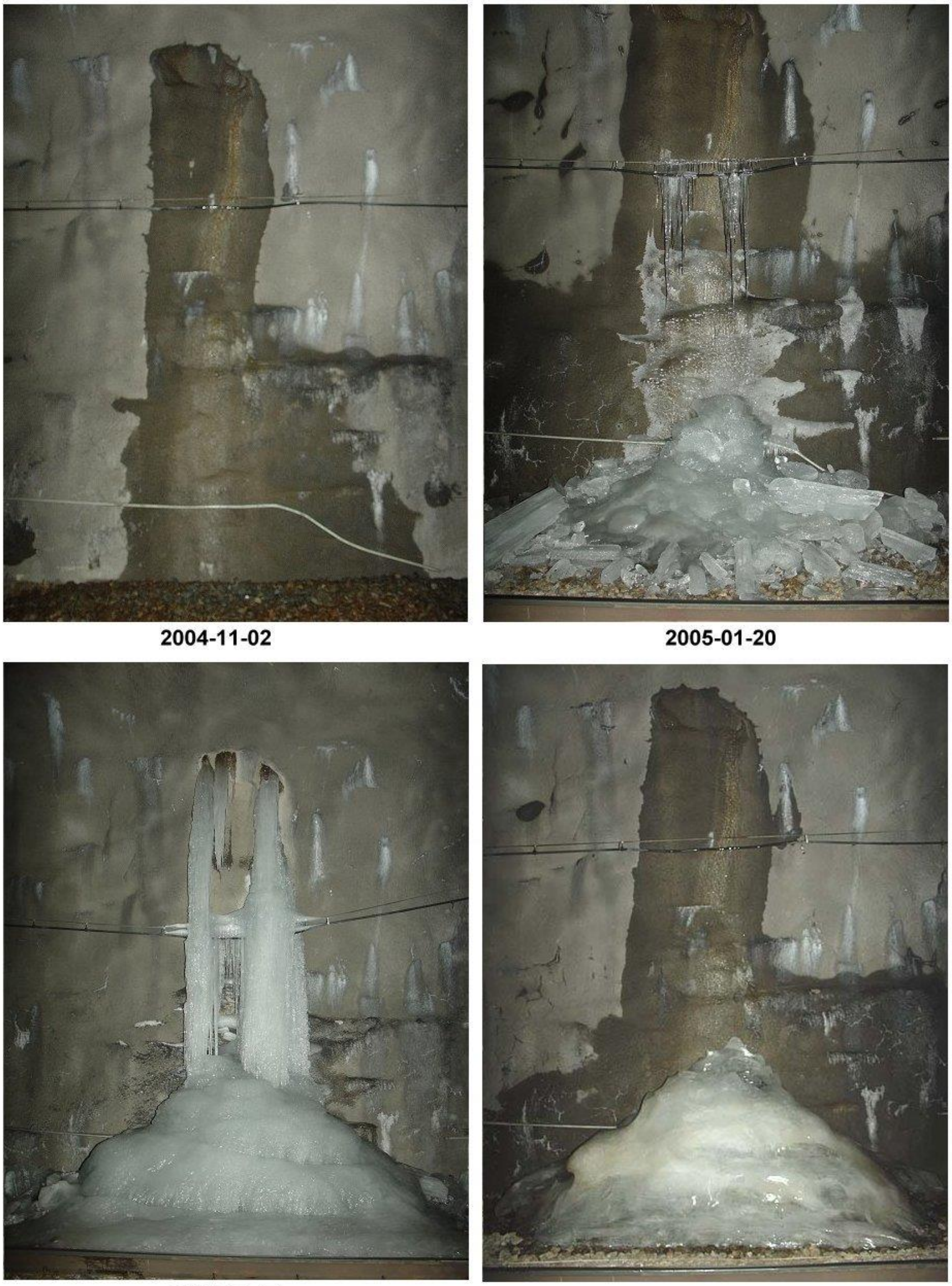
a) b)

Figure 19: a) Broken handrail near a leak, Glödberget chainage km 816+665 left, 2004-11-02 (Andrén, 2008). b) Cracked shotcrete and broken handrail, Glödberget chainage km 817+104 left, 2004-11-02 (Andrén, 2008).

In the roof at chainage km 816+597, shotcrete had been scaled and the rock surface was exposed. There were many water leakage points in the section and a large ice layer had formed over the track (Figure 20). The ice layer had been removed from the rails to prevent derailment.

Figure 20: Exposed rock surface after scrapping of shotcrete and ice layer at the track, Glödberget tunnel chainage km 816+597, 2005-01-20 (Andrén, 2008).

Chainage km 816+665 is a known problem spot for the maintenance workers (Figure 21). The section did not look like a problem spot, the shotcrete was not cracked, and the moisture was not spread over a particularly large area. But the handrail was broken, so this might be a problem spot. In the second inspection, the extent of the problem was clear, because an ice pillar had formed, ice layers were approaching the track and icicles were hanging on the cable. Despite the temperature in the tunnel, the leak continued, which meant that the ice pillar was still growing. There was significantly more moisture on the wall during the second inspection compared to the first. In the third inspection, water still leaked out of the leakage point and a very large ice pillar had formed that applied load to the cable in the left shoulder. The shotcrete on the wall was now dry, except around the leak itself. In the fourth inspection, the shotcrete was moist again and the ice pillar was slowly melting away.



2004-11-02

2005-01-20

2005-03-17

2005-05-19

Figure 21: Differences between the four inspections in the Glödberget tunnel, chainage km 816+665 left (Andrén, 2008).

3.5.6 Comparison over three years

To see how the occurrence of ice formations varied over different years, further follow-up inspections of the Glödberget tunnel were undertaken in March 2005, 2006 and 2007. These inspections showed an annual variation in the moisture and quantity of ice in tunnels. Figure 22 shows the difference in the size of the ice formation in a certain section during the three annual inspections.

2005-03-17 2006-03-22 2007-03-21

Figure 22: Comparison at chainage km 816+665 in the Glödberget tunnel in March 2005, 2006 and 2007 (Andrén, 2008).

The photos in Figure 22 also show the difference in moisture conditions on the tunnel wall. During the 2007 inspection, the shotcrete was much moister than in the two previous years, which can partly be explained by the fact that the temperature had fluctuated around 0°C for about a week before the inspection (Figure 23). This may have caused warmer outside air to penetrate the tunnel, thawing the rock mass nearest the tunnel wall and causing the leak to become active again.

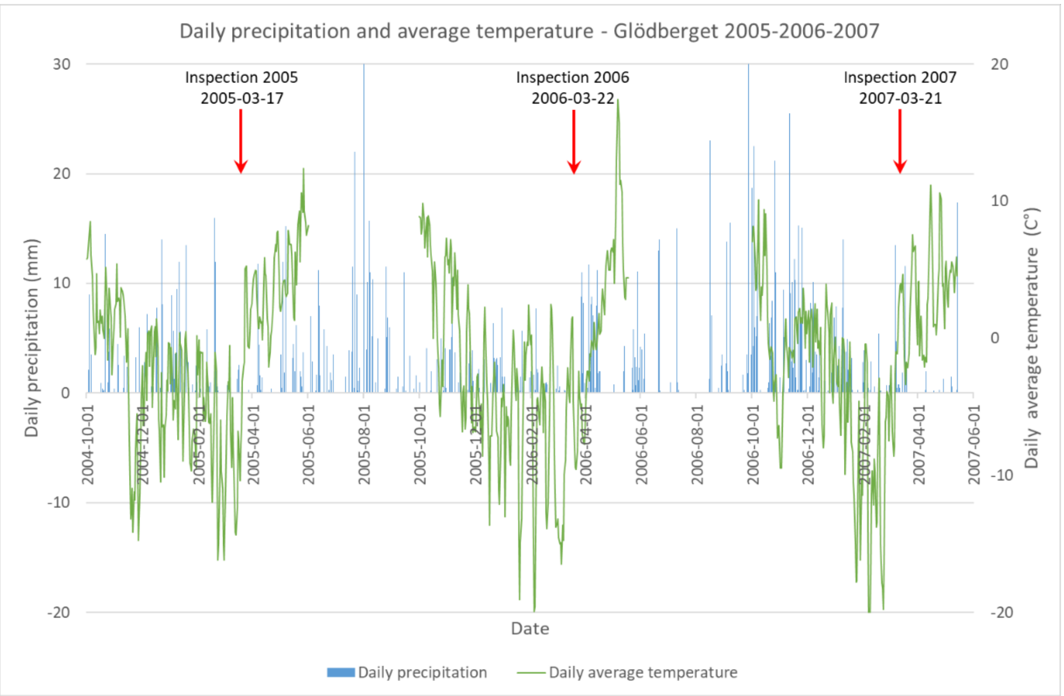
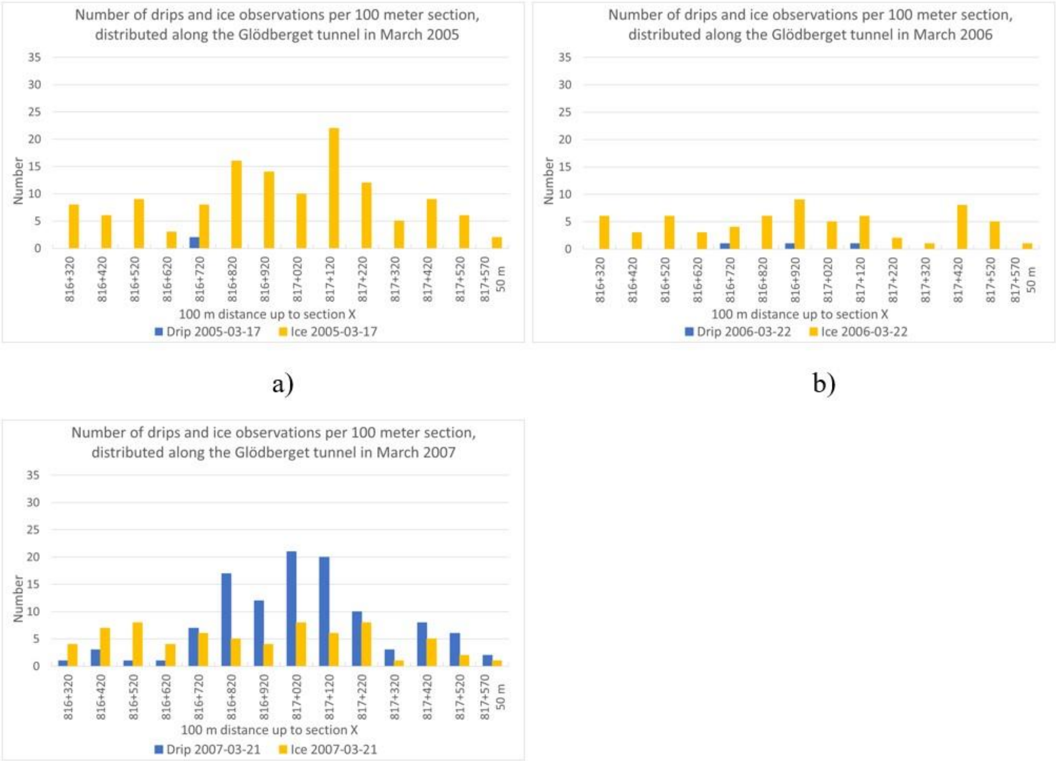


Figure 23: Daily average for precipitation and temperature for the Glödberget tunnel over three years.

Figure 24 shows the number of drips and ice observations along the Glödberget tunnel in March during the three years 2005, 2006 and 2007. The number of drip observations during the 2007 inspection was significantly more than during the previous two inspections, which probably reflects the temperature conditions before each inspection. Differences in the number of ice observations, and also the extent of the ice formations, can be explained by the fact that in 2004/2005 the beginning of winter was relatively mild and there were many temperature fluctuations around 0°C (Figure 23). The tunnel air was too warm to freeze the rock surface around the source of the leak, but cold enough to produce ice formations when the water reached the cooled tunnel wall or ballast surface. In 2006, the temperature fluctuations around 0°C were significantly fewer, and the temperature was relatively low for longer periods (Figure 23). This caused the leakage points to freeze, which led to fewer ice formations (compare yellow bars in Figure 24a and b). In 2007, the temperature fluctuated around 0°C until the beginning of January, when the temperature dropped rapidly, and a longer period of freezing temperatures started (Figure 23). The tunnel probably froze quickly, which led to fewer ice formations and the ice pillars were not so extensive (Figure 24c).



a) b)

c)

Figure 24: Number of drips and ice observations per 100 m section in the Glödberget tunnel, March 2005, 2006 and 2007.

In some sections, recurring problems were observed during the inspections in different years, while other occurrences were scattered along the tunnel and arose in different places during the three years. Once again, there was a great variation in the location of the drips and ice observations, despite the fact that the inspections were performed at the same time during each of the different years. This further highlights the problems of choosing the location of drains. The advantage of following up inspections over several years is that it becomes clear which problems are recurring and should, therefore, be prioritised for maintenance.

3.5.7 Discussion

In the Glödberget tunnel, the drips and ice formations do not follow the same pattern as in Nuolja and Laduberg, where the number of ice formations in relation to drips was greater further into the tunnel compared to the conditions at the entrances. The number of ice formations compared to drips in Glödberget has an even distribution over the entire length of the tunnel. One of the reasons for this might be that the tunnel has a 12‰ inclination, which creates a draft through the tunnel due to the chimney effect. This means that the cold penetrates the entire length of the tunnel in a different way than in Laduberg and Nuolja. Another reason may be that the

Glödberget tunnel has more drains than the other two tunnels (a total of 70% of the roof and the walls are covered with insulated drain mats), which prevents the heat from the rock mass from reaching the tunnel and warming up the tunnel air.

3.6 Results for the Rönninge tunnels

3.6.1 Facts about Rönninge

The three tunnels in Rönninge are located near Stockholm in the middle part of Sweden (Figure 5). The tunnels came into operation as early as 1915. The northern tunnel is 118 m long, the middle 32 m and the southern is 261 m. The distance between the northern and the middle tunnel is 58 m and the distance between the middle and southern tunnel it is 48 m. The tunnels were built with double tracks and have a width of 10 m and a height of 7 m above the top of the rail. The northern tunnel has an inclination of about 10 ‰ to the south, the middle tunnel rises slightly to the south, while the southern tunnel declines slightly to the south. The rock consists of gneiss with a strong mineral orientation, which gives a scaly structure. The rock has a high mica content, which is partly weathered. The rock cover is about 10-15 m.

3.6.2 Actions carried out in the Rönninge tunnels

The tunnels were reinforced with cast-in-place concrete arches as early as 1915 (Figure 25a). After a large rockslide in Rönninge in 1925, additional reinforcements were carried out between 1925 and 1927 using additional concrete arches. The rock surface in the rest of the tunnel is not reinforced except for some selective bolting, as well as some smaller surface support with rock safety mesh. There are sporadic drain mats installed along the tunnel. These are mainly located where the rock and the concrete arches are connected. They consist of uncovered PE mats that are fastened with bolts and some drain mats are covered with nets (Figure 25b).

a) b)

Figure 25: a) Cast-in-place concrete arches, Rönninge South chainage km 29+714 left, 2004-12-16 (Andrén, 2008). b) Uncovered PE mats Rönninge North chainage km 29+448 right, 2004-12-16 (Andrén, 2008).

Attempts have been made to lead the water away from the roof with metal plates lying on the beams between the concrete arches (Figure 26).

Figure 26: Sheet metal lying on beams between the concrete arches, Rönninge South chainage km 29+730, 2004-12-16 (Andrén, 2008).

3.6.3 Climate data for Rönninge

Temperature information was taken from the Swedish Transportation Administration’s weather data station No. 207 Salem and precipitation information from SMHI's climate station at Södertälje. Figure 27 shows the daily values for precipitation and average temperature for the winter period 2004-2005.

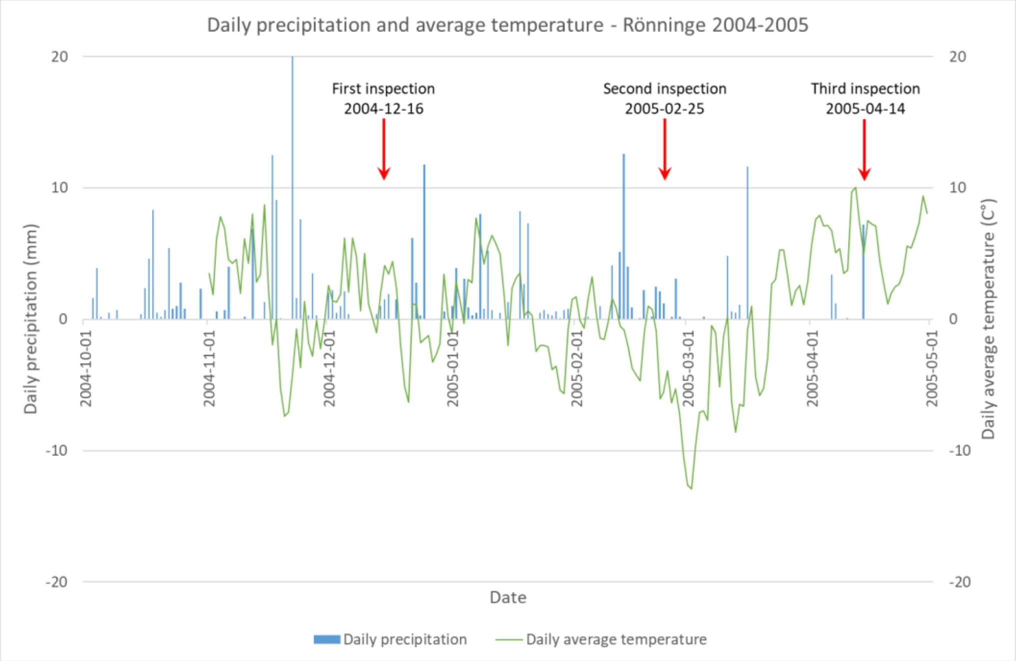


Figure 27: Daily average for precipitation and temperature.

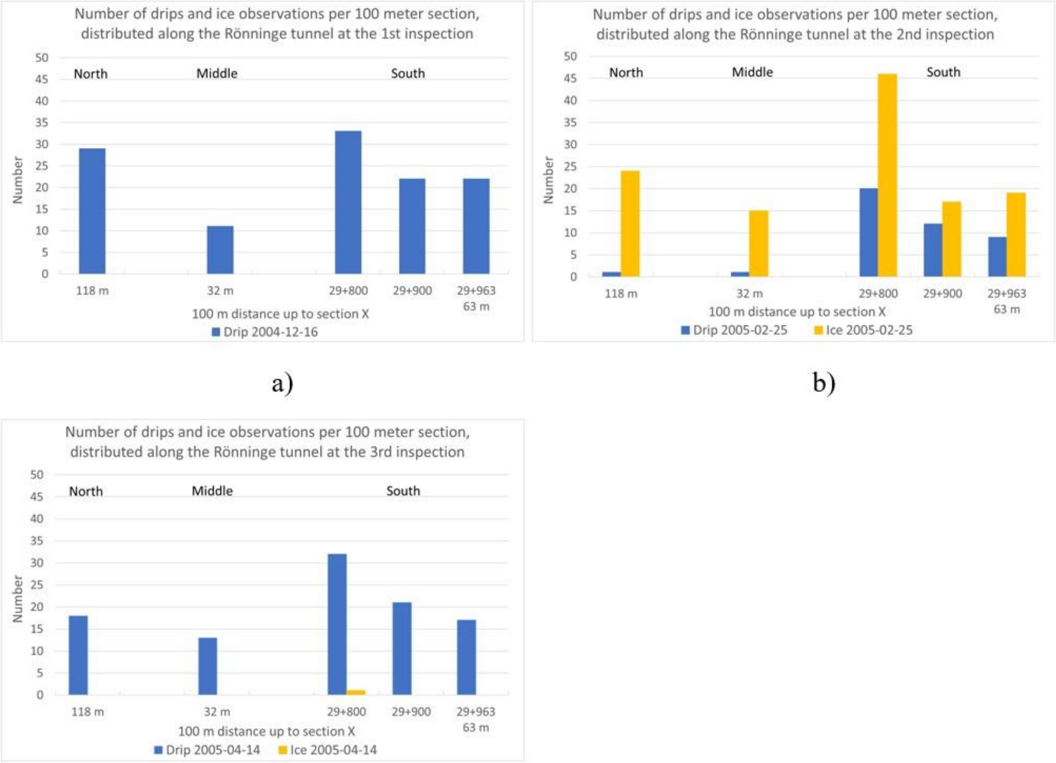
3.6.4 Results of the inspections in the Rönninge tunnels

In the first inspection on 16 December 2004, the temperature had been below freezing. However, in the days before the inspection, the temperature had risen above 0°C. There had not been much rainfall (Figure 27). The tunnels had moist surfaces, often where the rock mass and the concrete arches connected. There were several leakage points from the roof. In some places, attempts had been made to direct the water away from the roof with steel plates lying on beams between the concrete arches (Figure 26). These were rusty and broken, resulting in leaks on to the track area. For the north and south tunnel, the concentration of drips and moist surfaces was at the northern entrance (Figure 29a).

Between the first and the second inspections, the temperature had fluctuated around 0°C, with a large amount of ice forming as a result (Figure 27). Under these temperature conditions, maintenance inspections must take place every night to remove icicles and ice layers on the tracks, a very costly and time-consuming job. In the second inspection on 25 February 2005, there was only one leakage point still active in the two shorter tunnels (northern and middle), while in the southern tunnel there were more leakage points and moist surfaces. Adjacent to these leakage points, concentrations of ice were observed. This was especially the case in the northern entrance of the south tunnel, where there were leakage points along the entire roof and walls. Many icicles had formed here, as well as a large layer of ice on the track area (Figure 28). The concentration of ice formations matched closely the areas that had the most drip observations in the first inspection, compare Figure 29a and b.

Figure 28: Icicles at an active leakage point and ice layers on the tracks, Rönninge South chainage km 29+720 the first picture photographed to the south, the second to the north, 2005-02-25 (Andrén, 2008).

At the time of the third inspection on 14 April 2005, all the ice had melted in the two shorter tunnels, while in the southern tunnel there was still one ice formation. All tunnels were again moist with concentrations of water in the same places as in the first inspection, but to a somewhat lesser extent than before. According to the maintenance worker present, it had not rained for several days, which resulted in the tunnel not being as wet as it usually was (Figure 27). When comparing Figure 29a and c, the leakage in the northern entrance of the south tunnel is similar to the conditions that were observed in the first inspection.



a)

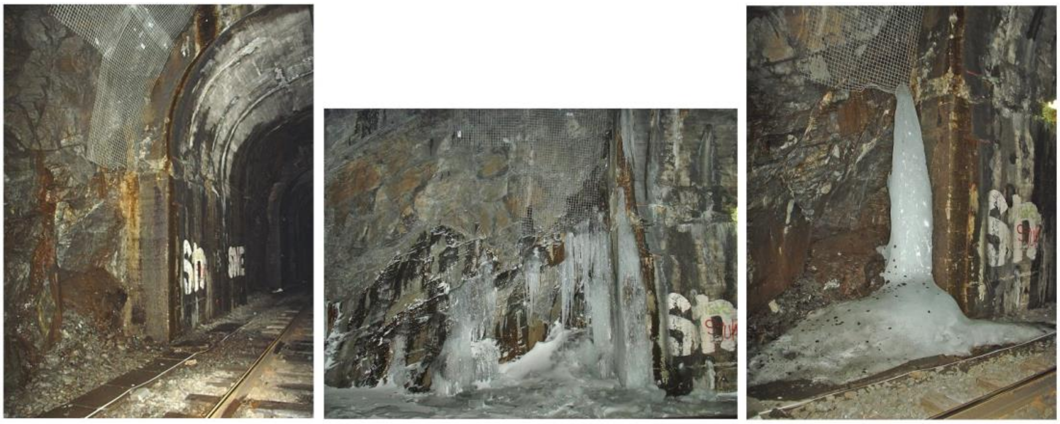
b)

c)

Figure 29: Number of drips and ice observations per 100 m section for the Rönninge tunnels, 2004/2005.

3.6.5 Photos from the inspections

Many leaks occurred where the rock and the concrete arches are connected and several of the leakages came from the joint planes along the entire tunnel. In the second inspection, several icicles/pillars had formed at the location of a leakage from a joint in the rock mass around chainage km 29+710. In the third inspection, many of the ice formations in the tunnel had melted, but there was still a large ice pillar adjacent to the concrete arc in this section. The extent of the ice pillar indicates that the leak had been active for a long time (Figure 30).



2004-12-16 2005-02-25 2005-04-14

Figure 30: Difference between the three inspections, Rönninge South chainage km 29+710 left (Andrén, 2008).

In the Rönninge tunnels, the majority of the ice observations were icicles in the roof (Figure 31). According to maintenance workers, Rönninge is one of the tunnels in the Stockholm regions that requires the most maintenance. During periods of negative temperatures, ice must be removed every night.

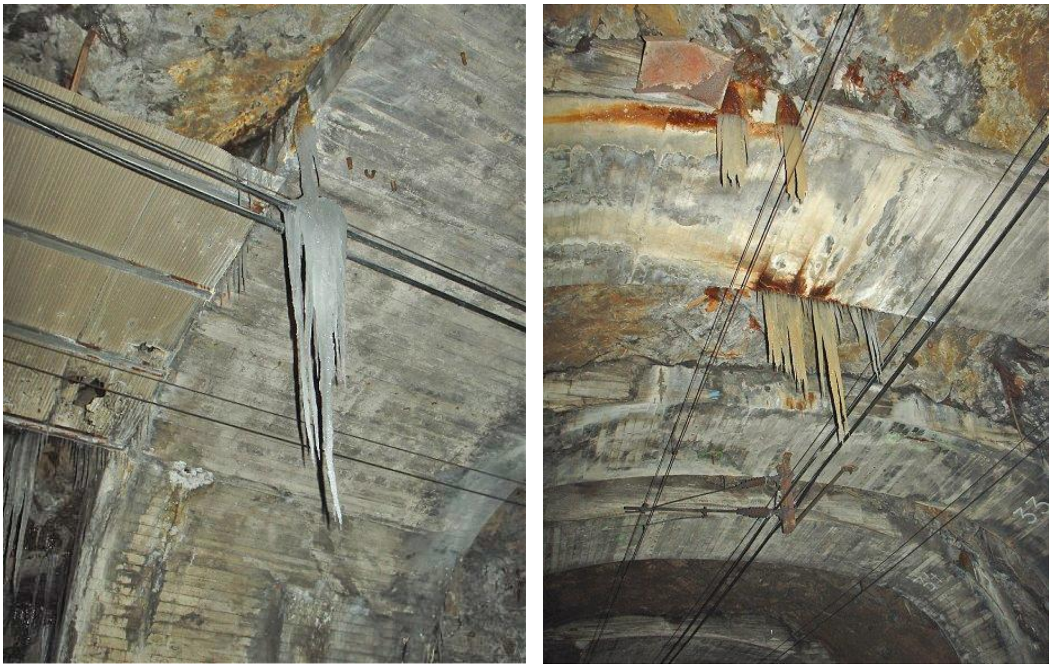


Figure 31: Rönninge South chainage km 29+734 and km 29+813 photographed to the south, 2005-02-25 (Andrén, 2008).

3.6.6 Discussion

The inspection diagrams from the Rönninge tunnels cannot be compared with the inspection diagrams from the longer tunnels in Nuolja, Laduberg and Glödberget. The Rönninge tunnels are significantly shorter, and the cold outside air is not heated by the rock mass. The Rönninge tunnels also have a different topography than the previous tunnels. Here the tunnels go through small outcrops and the rock cover is only about 10 m. The tunnels discussed above pass through mountains with significantly more rock cover, which generates more heat stored in the rock mass. In the Rönninge tunnels, the drips and ice observations were evenly distributed along the tunnel and the number of drip observations matched well to the number of ice observations within the same section.

3.7 Results for the Kvedesta tunnels

3.7.1 Facts about Kvedesta

The Kvedesta tunnels came into operation in 1995 and consist of the 52 m long northern tunnel and the 377 m long southern tunnel. They are double-track tunnels with a width of 11.5 m and a height of 7.4 m above the top of the rail. The tunnel declines with 10 ‰ towards the south. The bedrock consists mainly of sediment gneiss with slabs of fine-grained quartz-rich gneiss. In the southern tunnel, there are five major crushed zones where stronger reinforcement has been used. The rock cover is between 10-20 m.

3.7.2 Actions carried out in the Kvedesta tunnels

The railway tunnels were built without continuous pre-grouting. Only major crush zones were grouted. The frost insulation used consists of drains constructed from approximately 1 m wide insulation mats covered with mesh or fibre-reinforced shotcrete. In addition, uncovered drains have been set up with strips along the edges (Figure 32).

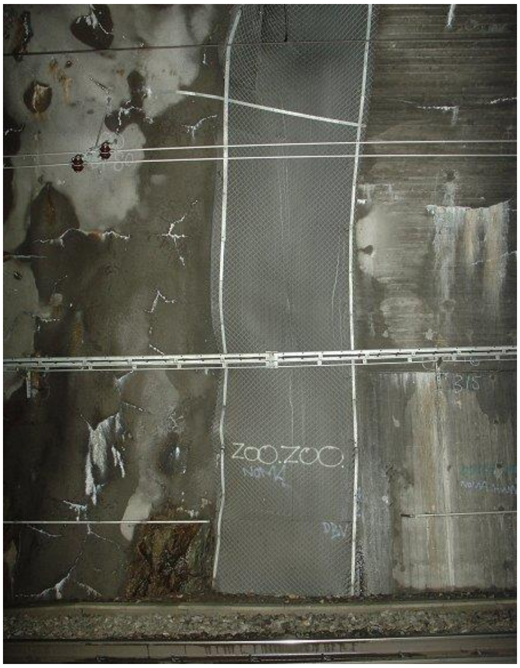


Figure 32: Uncovered drain, Kvedesta North chainage km 39+241 right, 2004-12-17 (Andrén, 2008).

3.7.3 Climate data for Kvedesta

Temperature information was taken from the Swedish Transportation Administration’s weather data station No. 203 Södertälje and precipitation information from SMHI's climate station at Södertälje. Figure 33 shows the daily values for precipitation and average temperature for the winter period 2004-2005.

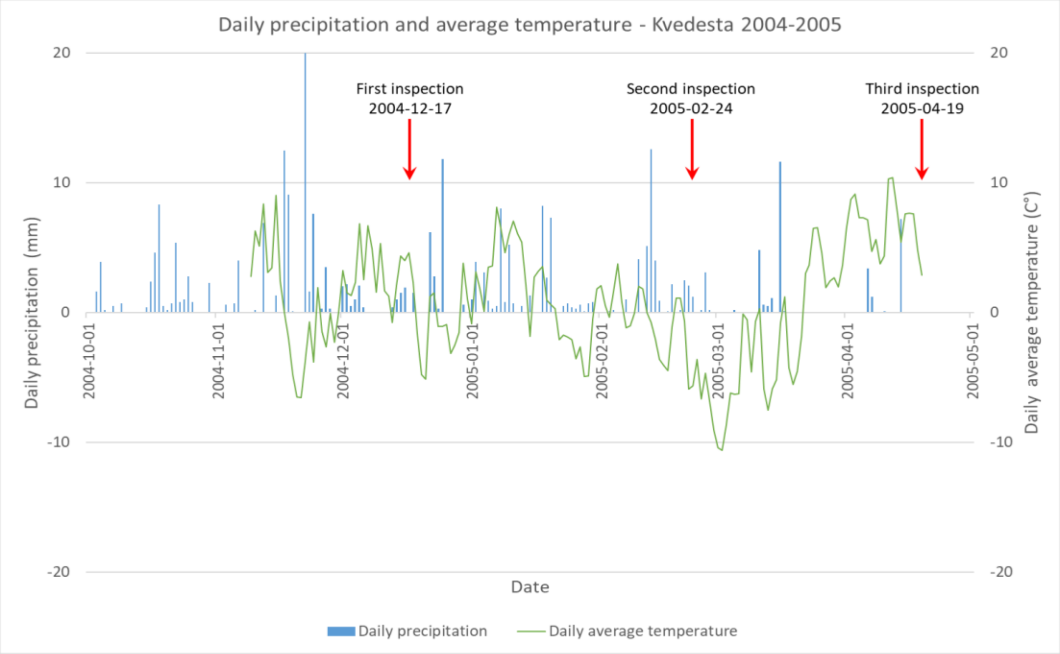


Figure 33: Daily average for precipitation and temperature.

3.7.4 Results of the inspections in the Kvedesta tunnels

Before the first inspection on 17 December 2004, the temperature had been below freezing, but the days before the inspection the temperature was over 0°C. There had not been much rainfall (Figure 33). In the first inspection, almost the entire northern tunnel had moisture on sections of the walls and roof and many drips were observed (red ellipse in Figure 34a). The southern tunnel had less moisture and the drip observations were concentrated around the roof near both the northern and southern entrances.

Between the first and the second inspections, the temperature had fluctuated around 0°C (Figure 33). Under these temperature conditions, maintenance inspections must take place every night to remove icicles and ice layers on the tracks. In the second inspection on 24 February 2005, only one leak was still active in the southern tunnel. In the northern tunnel, only four ice formations were observed, despite the fact that this tunnel had many leakage points during the first inspection (compare red ellipse in Figure 34a and b). In the southern tunnel, some ice formations were observed and they occurred, as the leakage points in December, near both the northern and southern entrances.

Before the third inspection on 19 April 2005, the temperature had been over 0°C and there was no ice left in the tunnels at the time of inspection. In the northern tunnel, there were leakage points in the roof and on the walls, but not to the same extent as in the first inspection (compare red ellipse in Figure 34a and c). In the southern tunnel, the concentration of leakage points was similar to the first inspection, near both the northern and southern entrances (compare the South tunnel in Figure 34a and c).

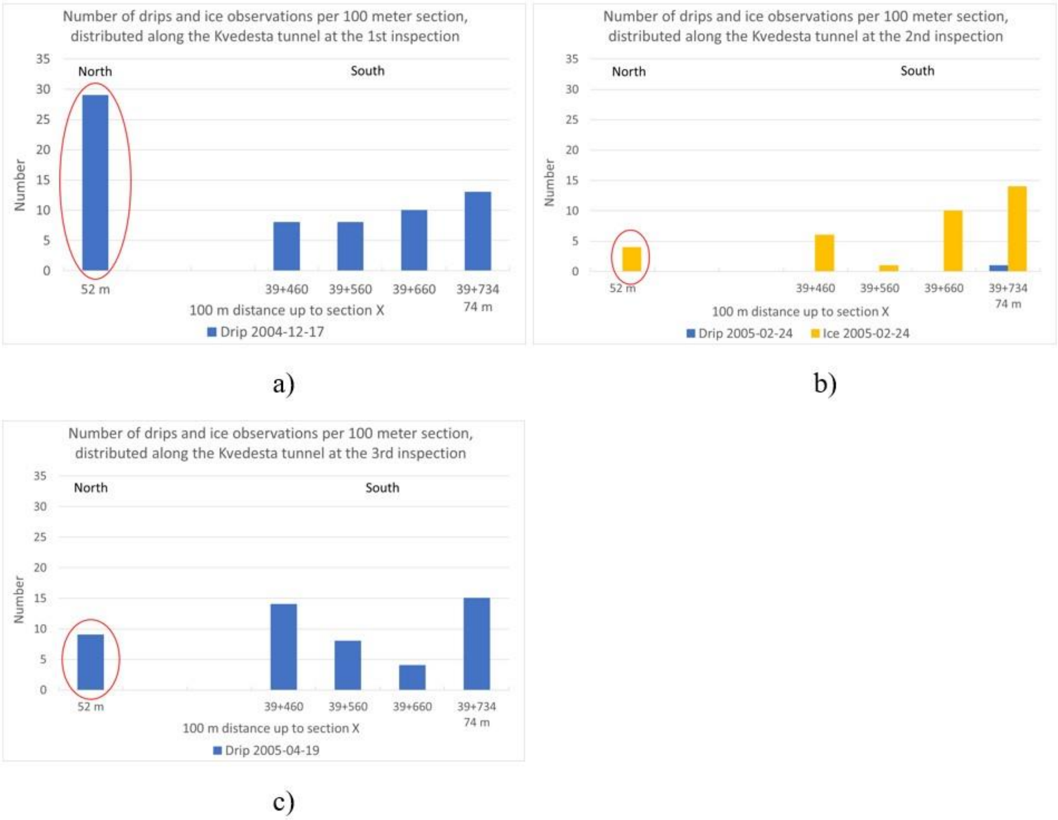


Figure 34: Number of drips and ice observations per 100 m section for the Kvedesta tunnels, 2004/2005.

3.7.5 Photos from the inspections

In several places in the Kvedesta tunnels, the shotcrete was cracked and there were moist areas in the shotcrete around the covered drains, which indicates that water was seeping out around the side of the drains (Figure 35).

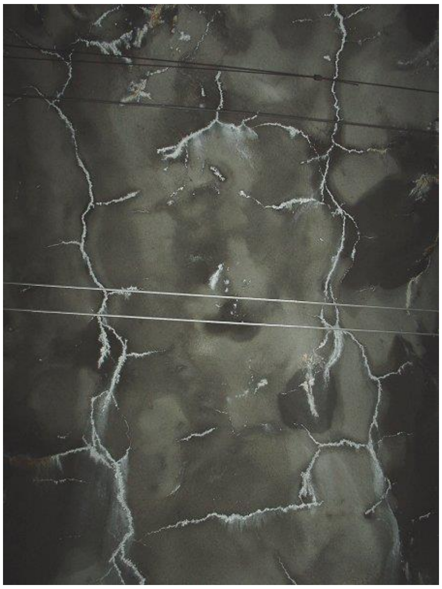


Figure 35: Cracks around a covered drain, Kvedesta South chainage km 39+372 left, 2004-12-17 (Andrén, 2008).

In the Kvedesta tunnels, one recurring problem was on the right side at chainage km 39+367 in the south tunnel (Figure 36). Ice must be removed from the electrical cabinet every cold period. This tunnel section is 10 m from the northern entrance and is, therefore, affected almost directly by the temperature changes outside the tunnel. In the first inspection, the entire wall was moist. In the second inspection, a large ice pillar had formed next to the electrical cabinet and pushed the cabinet out of its original position. In the third inspection, the tunnel was dryer, but the leakage point just above the electrical cabinet was active. Note the difference in the moisture on the wall between the first and last inspection.

2004-12-17 2005-02-24 2005-04-19

Figure 36: Differences between the three inspections, Kvedesta South chainage km 39+367 right (Andrén, 2008).

3.7.6 Discussion

The inspection diagrams from the Kvedesta tunnels can be compared with the inspection diagrams from the Rönninge tunnels, as they are both shorter tunnels and are located in a similar topography. The number of drip observations were evenly distributed over the entire length of the tunnels and corresponded to the number of ice observations within the same sections. Except at the northern tunnel, where the number of drip observations during the first inspection was significantly more than during the last inspection. It should be noted that despite many leakage points in the northern tunnel, not much ice is generated.

4. Discussion

During the field observations in Swedish railway tunnels, many problems with water and ice were discovered, all of which contribute to increased maintenance. The inspections have shown that water can continue to leak for a long time if the freezing rate is slow. The temperature changes and the duration of the freezing periods have a major effect on the number and location of leakage points and ice formations in a tunnel. If the freezing period has a long duration, some of the leakage points become frozen. The water freezes and ice formations are created, which act like a plug for the leak; it ’freezes dry’. If the leak is instead subjected to short periods of freezing and thawing, the joint will never become frozen and water will continue to leak, resulting in growing ice formations. The central and southern parts of Sweden have shorter cooler periods and the tunnels are exposed to many temperature fluctuations around 0°C during the winter. Frost does not penetrate into the tunnels in the same way as in the northern parts of Sweden. Therefore, more ice problems arise around the entrances of the tunnels in the southern parts of Sweden, than for those in the northern parts. For northern parts of Sweden, the problem of growing ice formations in sections near the tunnel entrance usually appears only during the autumn and spring and not during the winter. The field observations show that the problems with ice growth and temperature fluctuations around 0°C occur further in along the longer tunnels in the northern parts of Sweden, because the tunnel air temperature is higher due to heat transfer from the rock mass. Hence, water can continue to leak, and more ice is formed from leakage points in the inner parts of the tunnel than from the leakage points at the entrances, which tend to ’freeze dry’. For shorter tunnels that adopt the same temperature as the outside air, the number of ice formations are evenly distributed over the entire length of the tunnel and correspond to the number of drip observations within the same section. The extent of the leakage is of great importance for ice formation. The heat from the rock mass is transported by the water to the location of the leakage point. When the amount of the leakage is large, the heat content of the water keeps the rock unfrozen despite the freezing tunnel air temperatures and the water continues to flow. A small leak does not add enough heat and can, therefore, ‘freeze dry’, when the cooler air from the tunnel exceeds the heat content from the leaked water.

The field observations have shown that frost penetration and ice formations occur along the entire length of the tunnel, even in tunnels with lengths over 1000 m. The frost insulated drains, which are used to lead the water down to the drainage system on the tunnel floor, not only prevent the cold from reaching the location of the leakage point. They also prevent the rock mass from emitting geothermal heat that warms up the cold tunnel air. The frost can then penetrate further into the tunnel and problems with ice formations also develop in the inner parts of the tunnel. Many problems with frost insulated drain mats were observed during the inspections. Some of the problems are due to incorrect installation of the drains. Some drains do not reach all the way down to the tunnel floor and, therefore, the leaked water freezes before it reaches the frost-free drainage system on the tunnel floor. Ice formation can occur behind the drains, which can lead to frost shattering. Sometimes the edges of the drains have not been properly sealed, or the drains become clogged by chemical deposits or ice, which forces the water to take a different path. During these inspections, it was observed that many ice pillars arise from leaks next to drains. The ice pillars can grow so large that they encroach on to the gauge clearance. They must, therefore, be constantly monitored and removed when required. Icicles in the roof and ice layers in the middle of the track can developed when frost insulated drain mats only extend from one tunnel wall up to the middle of the tunnel roof. If the edge of the drain is not properly sealed, water can leak from the centre of the roof. This leads to icicles forming directly above the overhead contact line, or ice layers forming on the ballast surface and on the tracks. To prevent dripping within the track area, the drains should, therefore, be extended further out to the side and preferably all the way down the opposite wall down to the frost-free tunnel floor. Ice layers can develop when the magnitude of the leakage is so large that it cannot drain through the ballast bed and down on to the tunnel floor. One problem that was observed in the field observations was that the drains end above the ballast surface. The leaked water flows out on top of the ballast and forms ice layers. This problem can be avoided if the drains are installed all the way down to the tunnel floor. One positive example to control ice layers was carried out in the Laduberg tunnel. A heating cable was laid down along the tunnel wall and kept the ballast surface unfrozen so that the water could drain down to the frost-free tunnel floor. Leaks and ice also occur in joints between the drains and when, for example, brackets for handrails, cable racks and other installations pass right through the drain material and are not properly sealed. Ice formation puts an extra load on the installation itself, which can cause material failure. It is important that the Swedish Transport Administration provides maintenance workers with correct and updated documentation about where drains are located to avoid unnecessary puncture of the drains during installation.

The field observations showed that there was a difference in where and when leakage points appear during the year, and also in terms of the variation in the amount of leaked water. There was also a variation over different years. In different sections with relatively similar amounts of leakage during the autumn, a lot of ice could develop in one section during the winter, while in another section it could be completely dry with no ice formations. In another section, there was only moisture on the wall at the inspection in the autumn, but at the next inspection, a lot of ice had formed in that particular section. Therefore, the placement of drains is difficult to determine. The location of leakage points may move because the previous path has been sealed in a natural way. For example, in the Laduberg tunnel, in some sections where drains were removed and no new drains were installed, the rock surfaces were still dry after several years. That indicates that the paths for the leakage points had changed or that they may have been sealed naturally. One way to find out if the drains are working properly would be to use a thermal imaging camera to study which drains are still carrying water. First, the function of the drains should be checked during a period when there is a lot of water and moisture in the tunnel. The function of the same drain should then checked again during the cooler period to see if water is flowing behind the drain or if the leak has frozen or if the water is now flowing next to the drain. The conclusions of the field observations are that it is difficult to estimate where insulated drains should be located along a tunnel. Based on experience gained from this investigation, the location for drains should be decided after several inspections have been carried out and especially after a winter period, which is when the actual problems with ice formations occur.

5. Conclusions

The conclusions of the field observations are:

- Water can continue to leak for a long time if the freezing rate is slow.
- Temperature changes and the duration of freezing periods have a major effect on the number and location of leakage points and ice formations in a tunnel.
    - If the freezing period has a long duration, some of the leakage points become frozen. The water freezes and ice formations are created that act like plugs for the leaks; they ‘freeze dry’.
    - If the leak instead is subjected to short periods of freezing and thawing, the joint will never become completely frozen and water will continue to leak, resulting in ice formations.
- The extent of the water leakage affects the ice formation, because the heat from the rock mass is transported by the water to the location of the leakage point.
    - When the leak is large, the heat content of the water keeps the rock joint unfrozen despite the freezing tunnel air temperatures and the water continues to flow.
    - A small drip does not create enough heat and can, therefore, ’freeze dry’ when the cooler air from the tunnel exceeds the heat content from the leakage water.
- Frost penetration and ice formation often occur along the entire length of the tunnel, in this investigation even in tunnels with lengths over 1000 m.
- The frost insulated drain mats
    - lead the leaked water down to the drainage system on the tunnel floor.
    - prevent the cold from reaching the location of the leakage point.

  - prevent the rock mass from emitting geothermal heat that warms up the cold tunnel air, therefore, the frost can penetrate further into the tunnel and problems with ice formation also develop in the inner parts of the tunnel.
- Despite the use of drain mats, water and ice problems can occur, e.g.
  - If the drains do not extend all the way down to the tunnel floor, the leaked water freezes before it can drain through the ballast bed down to the frost-free tunnel floor. The leaked water flows out on top of the ballast surface and forms ice layers.
    - Action to prevent the problem: Drain mats should be installed so that they extend all the way to the tunnel floor. This can be combined with heating cables in the ballast bed, as was the case in the Laduberg tunnel.
  - If the edges of the drains have not been properly sealed, the cold air gets in behind the drain and ice formations can occur, which can lead to frost shattering of the drain material.
    - Action to prevent the problem: The edges of the drain mats must be properly sealed.
  - If the drains are clogged by chemical deposits or ice, the leaked water can take a different path moving the leak and any ice formation to the area beside the drains.
    - Action to prevent the problem: Flushing the drains in areas with known clogging problems and sealing the edges of the drain mats to prevent cold air getting behind the drain and to avoid leakage.
  - If the drain mats end at the roof or at the shoulders, icicles in the roof and ice layers in the area around the tracks can develop.
    - Action to prevent the problem: Drains must be properly installed and sealed along the edges. They should preferably be installed from the floor, over the roof and back down to the floor on the other side, at least they should not finish above the track area.
  - If the brackets for handrails, cable racks and other installations pass right through the drain material, leakage can occur if these openings are not properly sealed. Ice formation leads to an extra load on the installation itself, which can cause material failure.
    - Action to prevent the problem: It is important that maintenance workers have the correct and updated documentation about where drains are located to avoid unnecessary damage to the drain during installation. If a puncture of the drain cannot be avoided, the drain must be properly sealed once the work is completed.
- Variation of water and ice conditions during the inspections:
  - Leakage occurred at different locations and at different times during the year and the amount of leaked water also varied. There was also a variation over different years.
  - In different sections with relatively similar amounts of leakage during the autumn, large amounts of ice developed in some of the sections during

    the winter, while other sections were completely dry with no ice formations during the same period of time.
  - In another section, only moisture on the wall was observed at the inspection in the autumn and, at the winter inspection, large ice formations had been formed.
  - Overall, it is a complex and difficult task to decide where to install the drains.
    - The location of leakage points might occur at different positions at different times, because the path of the leaked water to an earlier spot in the rock mass has been sealed in a natural way.
    - The use of a thermal imaging cameras can show if water is flowing behind a drain during the cooler periods.
    - Based on experience gained from the field observations, the best location for drains should be decided after several inspections have been carried out and especially after a winter period, which is when the actual problems with ice formations occur.
- Different ice problems occur depending on the winter climate.
  - Shorter tunnels can adopt the same temperature as the outside air and the number of ice formations are, therefore, evenly distributed over the tunnel length and correspond to the number of drip observations within the same section.
  - Longer tunnels in the northern parts of Sweden.
    - The problem of growing ice formations in the sections close to the tunnel entrances usually occur only in the autumn and spring and not during the winter because they ’freeze dry’.
    - Problems with ice growth and temperature fluctuations around 0°C occur further in along the longer tunnels in the north, because the tunnel air temperature is higher due to heat transfer from the rock mass. Hence, more ice is formed from leakage points in the inner parts of the tunnel than from the leakages near the entrances.
  - Longer tunnels in the central and southern parts of Sweden.
    - The cooler periods are shorter than in the northern parts of Sweden and the tunnels are exposed to many temperature fluctuations around 0°C during the winter.
    - Frost does not penetrate into the longer tunnels in the same way as in the northern parts of Sweden.
    - More ice problems arise near the entrances of tunnels in the southern parts of Sweden than for the tunnels in the northern parts.

ACKNOWLEDGEMENTS

Thanks to The Swedish Transport Administration, the Swedish Research Council for Sustainable Development FORMAS and the Rock Engineering Research Foundation BeFo for supporting this study. We would also like to thank the persons in the reference group: Tommy Ellison/Besab, Johan Funehag/Luleå University of Technology and Tyréns, Thomas Dalmalm/The Swedish Transport Administration and Per Tengborg and Patrik Vidstrand/Rock Engineering Research Foundation BeFo.

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