

Evaluation of a laboratory model test using field measurements of frost penetration in railway tunnels

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ABSTRACT

Despite extensive grouting efforts to prevent water from leaking into tunnels, water seepages remain. When exposed to freezing temperatures, ice formations occur. During the winter, the Swedish Transport Administration's railway tunnels are affected by major problems caused by ice, such as icicles from roof and walls, ice loads on installations, ice-covered tracks and roads, etc. To ensure safety and prevent traffic disruptions, many tunnels require extensive maintenance. Improved knowledge about frost penetration in tunnels is required to reduce maintenance of the tunnels. Frost insulated drain mats are often used at leakage spots to prevent ice formation along the tunnels. To find out which parts of a tunnel are exposed to freezing temperatures, the University of Gävle and the Royal Institute of Technology in Stockholm conducted a laboratory model test on behalf of the Swedish National Rail Administration (now the Swedish Transport Administration). The laboratory model test aimed to find a method to determine the expected temperature conditions along a tunnel to decide which parts of the tunnel require frost insulation to protect the drainage system from freezing and prevent ice formation. To evaluate the laboratory model test, the Swedish Transport Administration in collaboration with Luleå University of Technology have performed field surveys in two Swedish railway tunnels. The field measurements involved monitoring temperatures in air, rock surfaces and rock mass, as well as measuring wind direction, wind and air velocity and air pressure. The measurements in the tunnels show that the frost penetrates further into the tunnels than was expected from the laboratory model test, which was based on a completely uninsulated tunnel. Frost insulated drains do not only prevent the cold air from reaching the rock mass, but also prevent the rock from emitting geothermal heat that warms up the cold tunnel air. Consequently, the frost penetrates further into the tunnel than it would do if the heat from the rock mass was allowed to warm up the outside air on its way into the tunnel. The number of frost insulated drains and how much of the tunnel walls and roof are covered thereby affect the length of the frost penetration.

1. Introduction

1.1. Background

The Swedish Transport Administration normally uses pre-grouting to seal tunnels, partly to meet environmental requirements but also to meet functional requirements on leakage as listed in the current regulations (Swedish Transport Administration, 2021). In areas that do not meet the functional requirements despite grouting, insulated water and frost-protection systems are installed to prevent dripping and ice formation in the traffic space. Water and frost-protection systems consist of insulating sealing membranes (for example, insulated drain mats), which

fulfill two purposes. The first is to prevent the cold tunnel air from reaching a leakage spot and causing water to freeze. The second is to divert the water from the traffic space down to the tunnel floor to be channelled out of the tunnel in a frost-free manner. The Swedish Transport Administration conducts ongoing work to develop programs and techniques to reduce and streamline maintenance in the tunnels. As part of that work, studies have been conducted to find out the expected temperature conditions along a tunnel, for example, long-term field measurements of temperatures in railway tunnels (Andrén et al., 2020; Andrén, 2008–2016). The purpose of the long-term field measurements was to provide a basis for increased understanding of temperature flow and frost penetration in tunnels, and to evaluate rules regarding water

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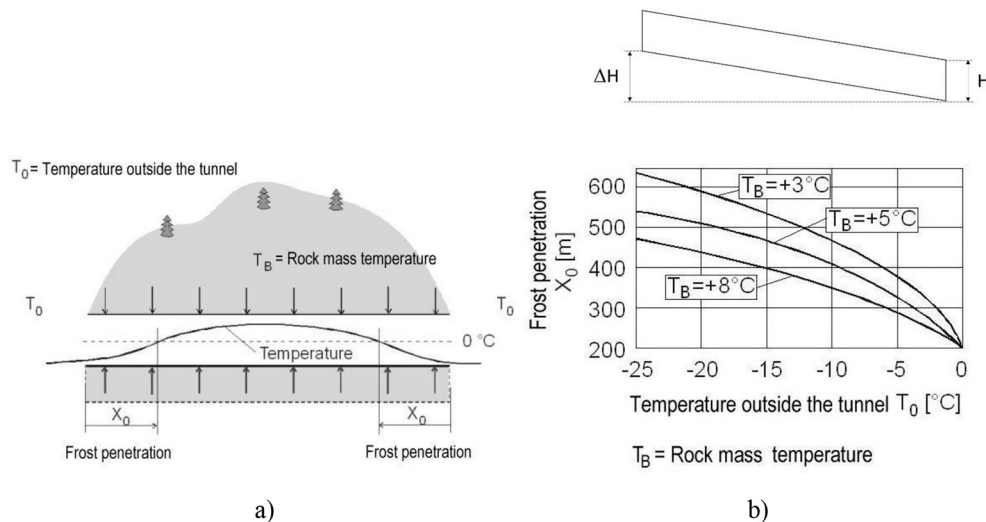


Fig. 1. a) Variation in temperature along a tunnel b) Frost penetration at the lower entrance of an inclined tunnel $\Delta H > 2H$ (both figures modified from Sandberg et al., 2002).

and frost in current regulations. The long-term field measurements were also used to evaluate the validity of the results from a laboratory model test performed by Sandberg et al. (2002), by comparing the laboratory model test results with the actual measured temperature conditions.

1.2. Previously performed laboratory model test

Sandberg et al. (2002) carried out a laboratory model test on behalf of the Swedish National Rail Administration. The aim of the laboratory model test was to investigate thermal conditions along a railway tunnel, evaluate the conditions that control thermal conditions and to identify which parts of a tunnel are not exposed to freezing temperatures. The Swedish National Rail Administration wanted a dimensioning method for frost protection for drains and the load-bearing main system from a maintenance perspective. Model tests were performed to verify or reject analytical theories used to estimate airflow and heat transfer in rock tunnels. The design of the tunnel model varied with respect to tunnel height and slope, as well as the air temperature outside the tunnel model and the ambient temperature inside the tunnel. Air temperature, velocity and direction were measured in the various test setups of the model tunnel.

Sandberg et al. (2002) considered that the frost penetration in a tunnel occurs when the tunnel air is set in motion by:

- **Thermally induced airflow:** the temperature of the rock mass and the outside air are different. The heat from the rock mass warms up the cold outside air entering the tunnel. The tunnel air becomes warmer and lighter than the outside air, thus creating a pressure difference that generates an airflow (chimney effect).
- **Train passing through the tunnel:** the airflow depends on the length and shape of the tunnel, the length and speed of the train set, the air and tunnel wall friction and the area of the train in relation to the tunnel area.
- **Wind pressure:** this occurs because the wind exerts a pressure on the tunnel air and generates a pressure difference between the tunnel entrances.

Sandberg et al. (2002) concluded that in a majority of the tunnels, the predominant cause of frost penetration is the thermally induced airflow. Even though the air velocity is not necessarily high, it has a major impact on the tunnel temperature since it is continuous and fairly constant. However, for short tunnels in which the height difference between tunnel entrances is relatively small, the laboratory model test results show that the dominant airflow is generated by the outside wind conditions. The whole tunnel can be exposed to the same temperature conditions as outside the tunnel. Airflow due to train traffic was found to have little impact on frost penetration.

The results of the laboratory model test form the basis for a number of temperature charts that show how frost penetration varies for tunnels with different inclinations. Fig. 1a shows the variation in temperature along a tunnel where frost penetration occurs along a certain distance (X_0) from the tunnel entrance to the section where the temperature rises above 0°C . The frost penetration distance (X_0) depends on the air temperature outside the tunnel (T_0) and the ambient rock mass temperature (T_B). The ambient rock mass temperature is normally dictated by the yearly average temperature in the part of Sweden where the tunnel is located (Erlström et al., 2016). In Fig. 1b, the curves represent typical ambient rock mass temperature for different climate zones in Sweden (Swedish Transport Administration, 2021). The upper curve represents the rock temperature for the north of Sweden ($T_B = +3^\circ\text{C}$) and the lower curve for the south of Sweden ($T_B = +8^\circ\text{C}$). Sandberg et al. (2002) produced different charts for different tunnel inclinations. The chart in Fig. 1b applies specifically to the frost penetration at the lower entrance of an inclined tunnel where $\Delta H > 2H$, where ΔH is the total difference in altitude of the tunnel entrances and H is the height of the tunnel section. This is comparable to the situation in the Glödsberget tunnel, which is used for comparison in this article.

2. Field survey

2.1. Selected tunnel

To better understand frost penetration and evaluate the previous laboratory model test, the Swedish Transport Administration in

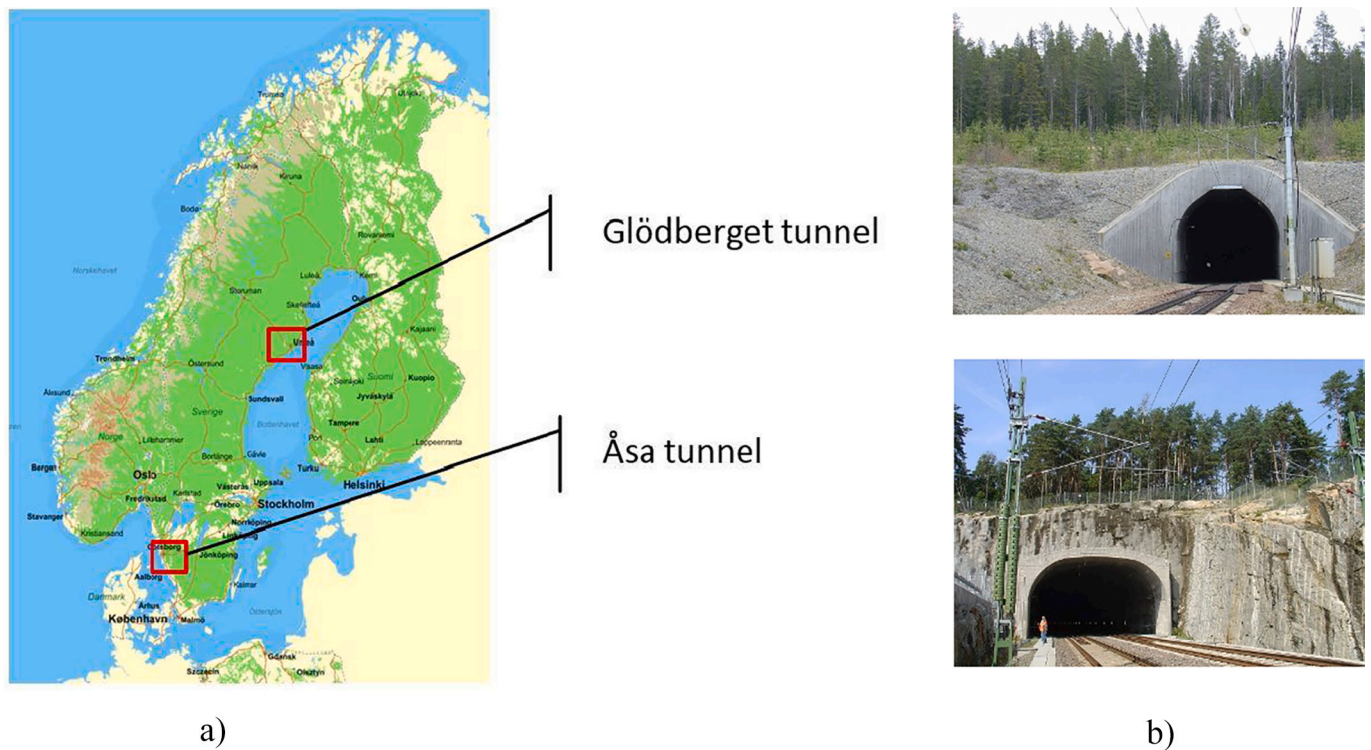


Fig. 2. a) Map of the locations of the Glödborget and the Åsa tunnels b) Top picture: The Glödborget tunnel. Bottom picture: The Åsa tunnel.

collaboration with Luleå University of Technology performed field measurements in two railroad tunnels located in different climate zones in Sweden (Andrén and Dahlström, 2011; Andrén et al., 2020; Andrén, 2008–2016). These tunnels were the Åsa tunnel in southern Sweden and the Glödborget tunnel in northern Sweden (Fig. 2a and b). The location of the measurement stations in the tunnel are given in accordance with the Swedish Transport Administrations chainage system. The chainage for the Åsa tunnel starts from Gothenburg and the Glödborget tunnel

starts from Stockholm. The Åsa tunnel is located 20 km and 100 m south from a specified zero point in Gothenburg (km 20 + 100) and Glödborget tunnel is 816 km and 160 m north of a specified zero point in Stockholm (km 816 + 160).

This article is primarily based on the results from the Glödborget tunnel, since this tunnel has a constant inclination from south down towards north, which makes it easier to directly compare with the laboratory model test, as opposed to the Åsa tunnel that has a low point

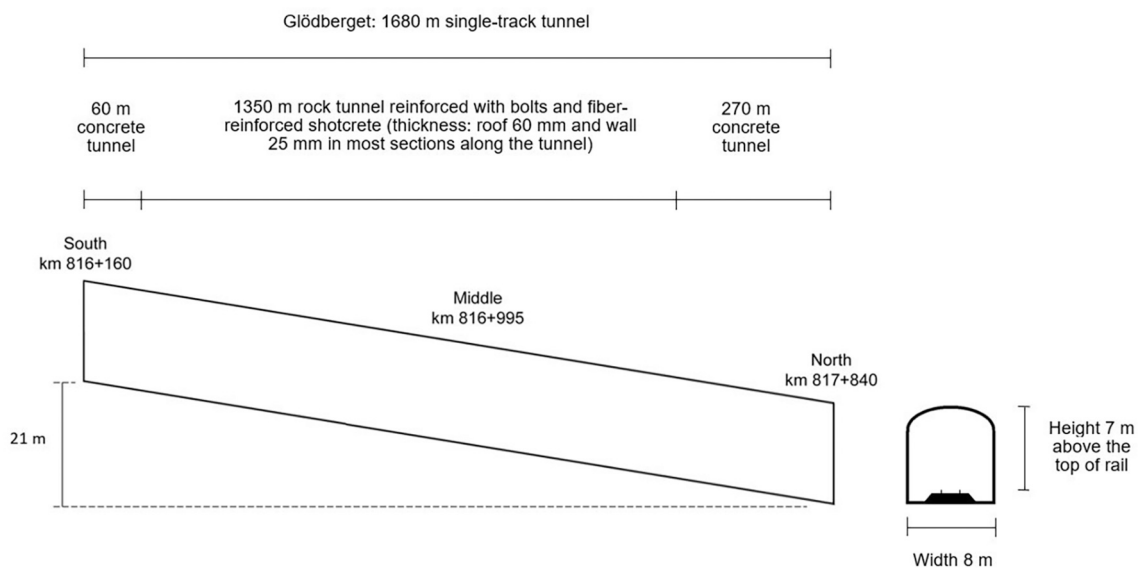


Fig. 3. Information and longitudinal sketch of the Glödborget tunnel (not to scale).

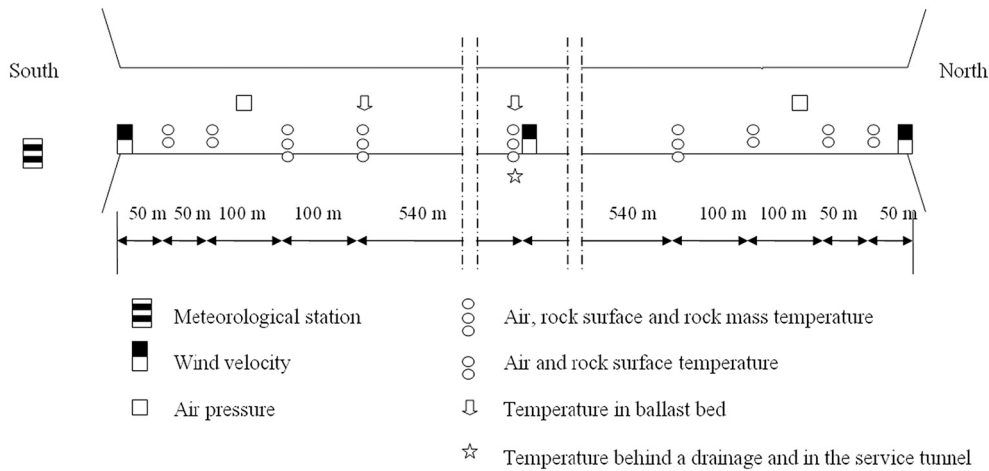


Fig. 4. Configuration and outline of the monitoring system installed in the Glödsberget tunnel.

about one-third into the tunnel from the north. Results from the Åsa tunnel are used in chapter 3.5.2. More information and results from the Åsa tunnel and the Glödsberget tunnel are reported in Andrén et al. (2020) and Andrén, (2008–2016).

The Glödsberget tunnel is a 1680 m long single-track tunnel, 80 km southwest of Umeå (Fig. 2a). The elevation difference (ΔH) between the higher south entrance and the lower north entrance is 21 m, which leads to a constant inclination of 12.5‰ (Fig. 3). In the Glödsberget tunnel, a total of 70% of the walls and the roof are covered with 140 mm thick insulated drain mats. They are distributed by 20% in the southern third, 48% in the middle third and 2% in the northern third.

2.2. Field test configuration

The monitoring system was installed in the Glödsberget tunnel in February 2007. It measures air and rock surface temperatures at nine sections along the tunnel. The total configuration and outline can be seen in Fig. 4. For more information about the field test configuration and the measurements, the following publications are recommended: Andrén et al. (2020) and Andrén, (2008–2016).

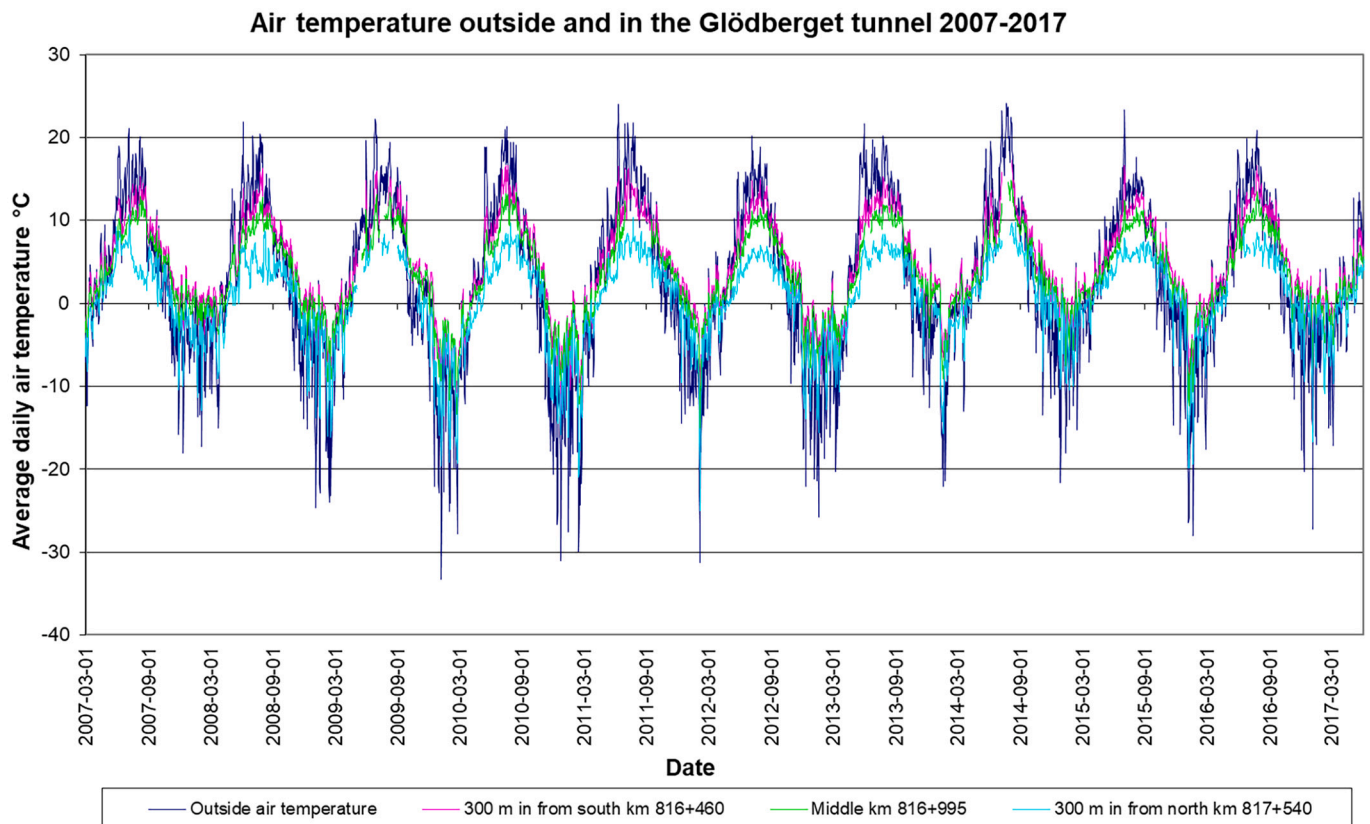


Fig. 5. Average daily air temperatures outside and inside the Glödsberget tunnel 2007–2017.

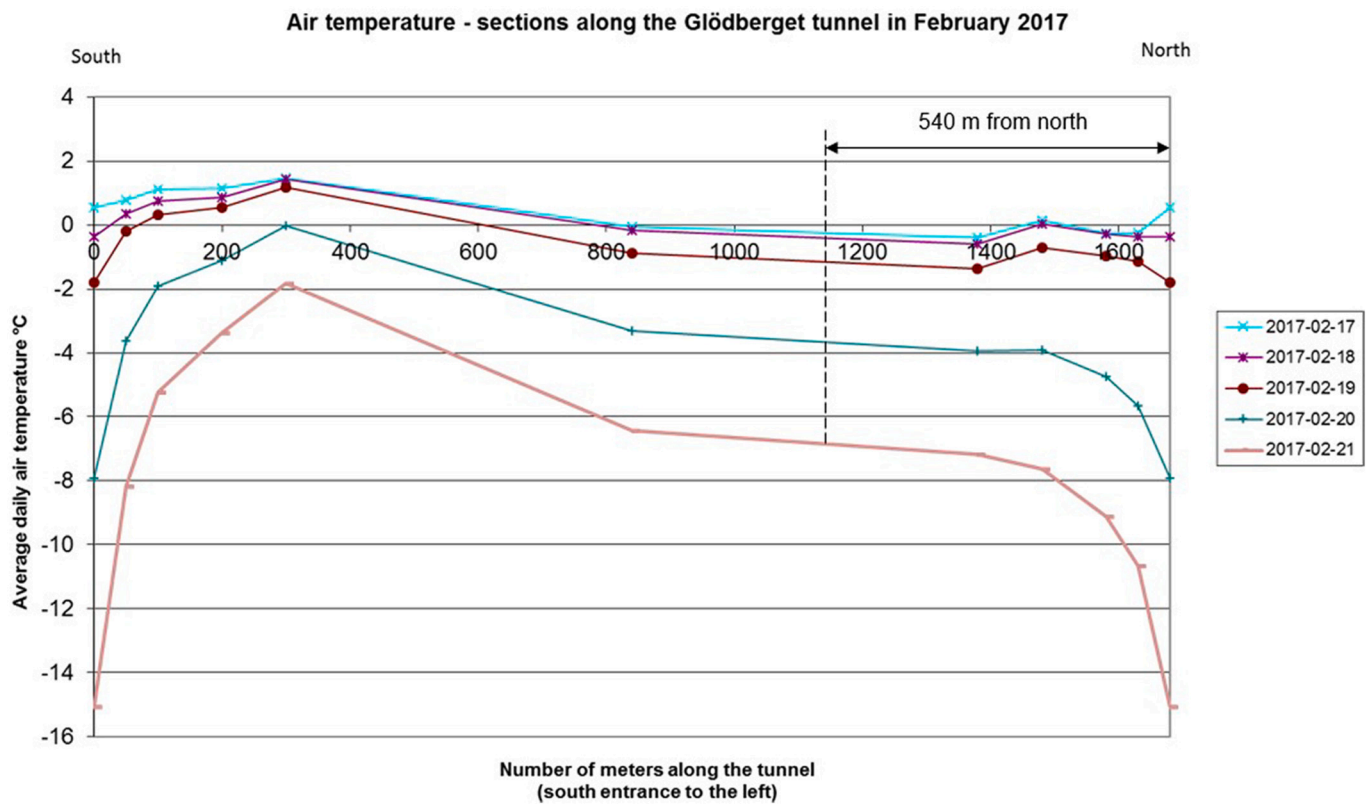


Fig. 6. Air temperature in the Glödborget tunnel for five consecutive days in February 2017.

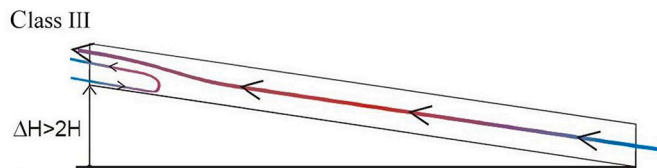


Fig. 7. Airflow pattern for Class III Case D (modified from Sandberg et al., 2002).

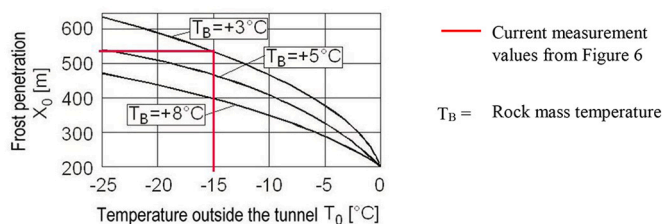


Fig. 8. Frost penetration from the lowest tunnel entrance in the Glödborget tunnel compared to Class III Case D (modified from Sandberg et al., 2002).

3. Results of field measurements and comparison with the laboratory model test

3.1. Comparison of frost penetration along the tunnel measured in the field and frost penetration evaluated in the laboratory model test

Measurements of the temperature of the tunnel air and the rock surface were performed to evaluate how far freezing temperatures penetrate into the tunnel and to evaluate the temperature difference and heat transfer coefficient in current conditions. Temperatures in the tunnel were measured from 2007 to 02-21 to 2021-04-30. Fig. 5 shows the calculated average daily air temperatures from 2007 to 03-01 to 2017-06-01, and the measurement stations in the tunnel are represented by different colours. The chart provides an overview of how the temperatures have varied over the years.

Fig. 6 shows the air temperature variation along the Glödborget tunnel during five consecutive days in February 2017. The higher southern entrance is to the left-hand side of the chart and the northern entrance to the right. The field measurements show that freezing temperatures penetrate further into the tunnel than previous assumptions made in the laboratory model test (Sandberg et al., 2002), and it penetrates further into the tunnel from the northern entrance than from the southern entrance. Despite the fact that the Glödborget tunnel is 1680 m long, frost penetrates the entire length of the tunnel even at a few negative degrees outside the tunnel.

The tunnel air, heated by the rock mass, moves by convection

Air temperature behind a frost insulated drain in the middle of the Glödsberget tunnel 2009-2011

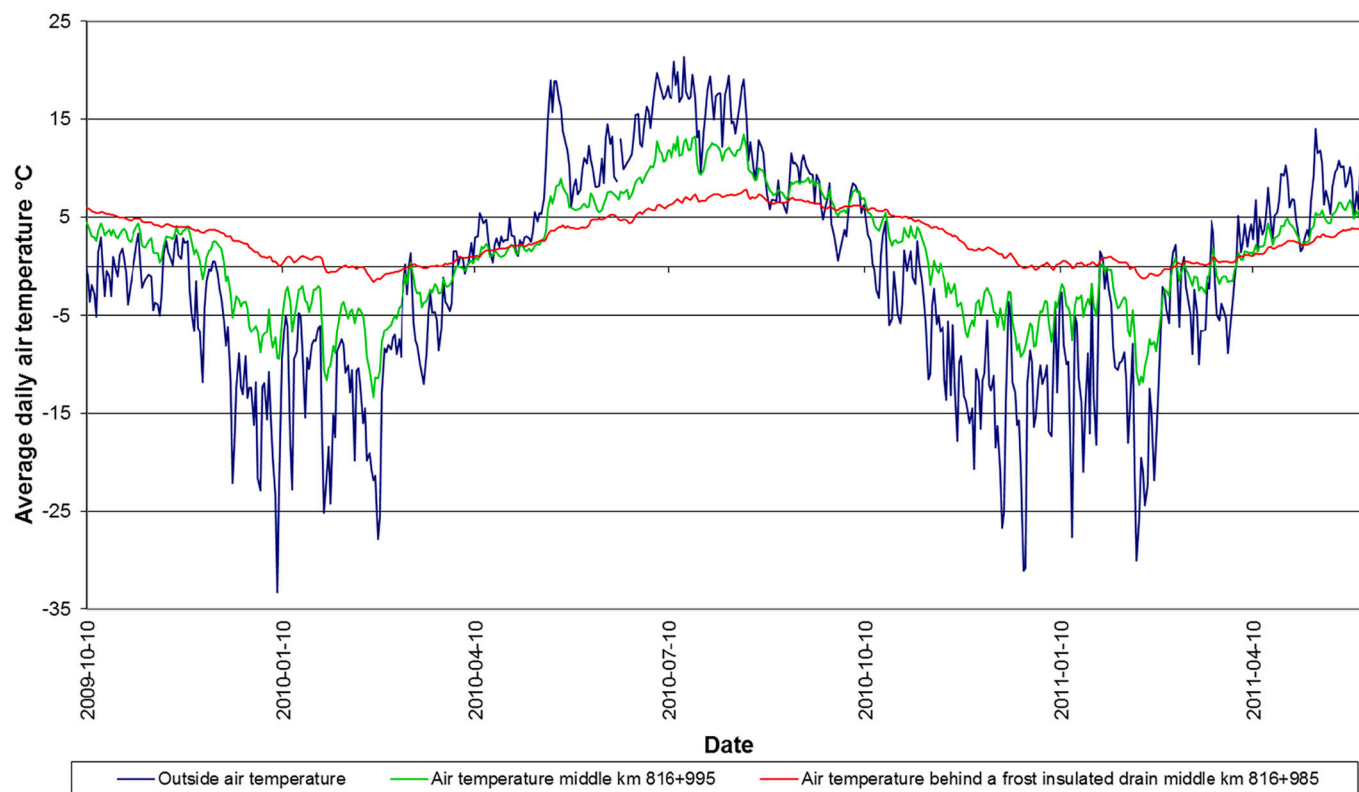


Fig. 9. Temperature behind a frost insulated drain mat, Glödsberget 2009–2011.

Wind and air velocity outside and inside the Glödsberget tunnel 2007-2012

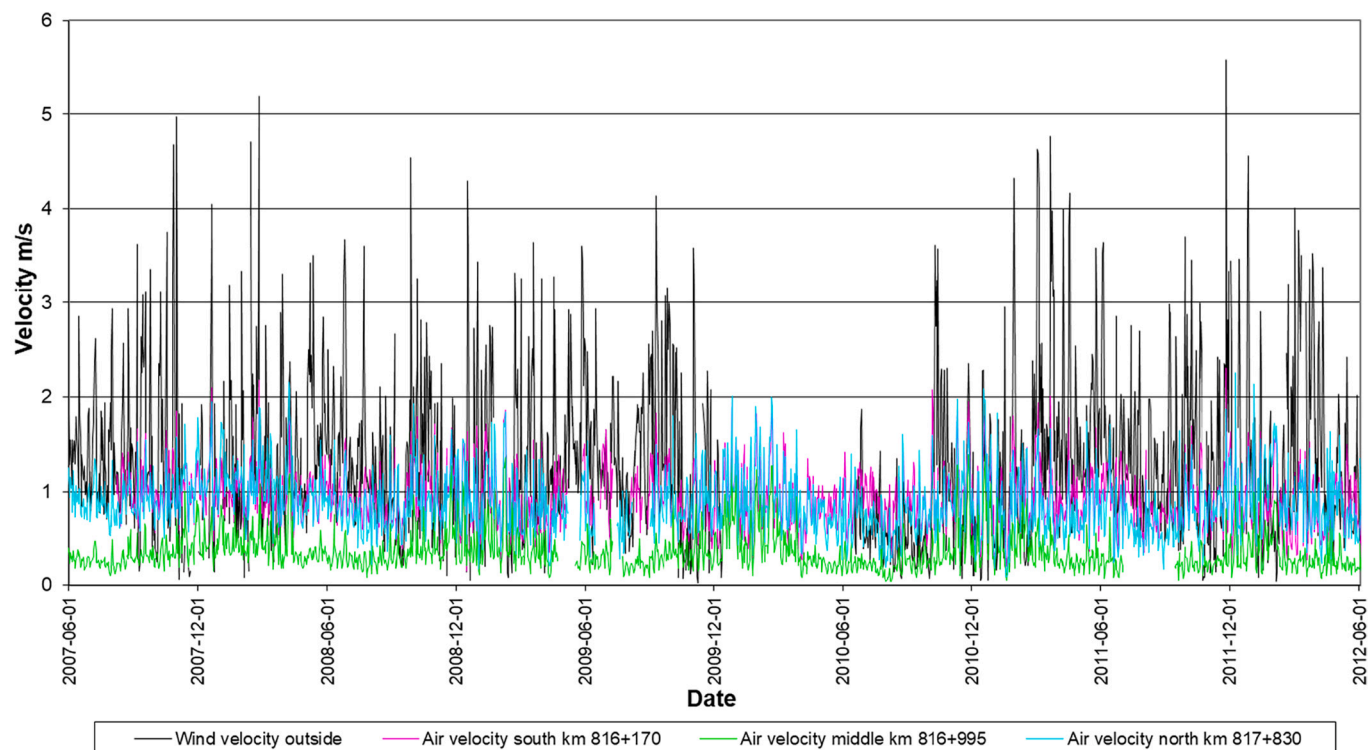


Fig. 10. Wind and air velocity outside and inside the Glödsberget tunnel during 2007–2012.

towards the southern tunnel entrance, located at a higher altitude than the northern entrance, resulting in higher temperatures in this part of the tunnel (Fig. 6). This result was also observed in the laboratory model test for the tunnel category Class III case D (where $\Delta H > 2H$). This category matches closely to the situation in the Glödsberg tunnel, where $\Delta H = 21$ m and $H = 7.2$ m. Fig. 7 shows that air flows in one direction in most parts of the tunnel and the heated tunnel air (blue line for cold air, turning red for heated air) rises to the higher entrance. At the higher entrance, cold air is entering the tunnel along the tunnel floor and creating a wedge of cold air. When this air is heated, the air direction changes and warm air rises towards the higher entrance again (Sandberg et al., 2002).

To make a comparison between the field measurements and the laboratory model test, the lowest outside temperature is selected from the temperature curve in Fig. 6. With an outside temperature of -15 °C and a rock mass temperature of $T_B = +3$ °C (see section 1.2 and Swedish Transport Administration, 2021), the red lines in Fig. 8 show that, according to the laboratory model test, the frost penetration should only reach about 540 m from the lower tunnel entrance for an inclined tunnel Class III. However, the field measurement shows freezing temperatures along the entire length of the tunnel (Fig. 6).

3.2. Temperatures behind a frost insulated drain mat and the effect of drains on the frost penetration

As described earlier (section 2.1), a large number of drain mats are installed in the walls and roof of the Glödsberg tunnel. In the middle of the Glödsberg tunnel (chainage km 816 + 985), a temperature sensor is installed behind a frost insulated drain mat on the tunnel wall (Andrén et al., 2020). To assess the insulation effect of the drain mat, and to observe if freezing occurs during different temperature conditions, the air temperatures in the tunnel and behind a drain mat (heated by the

rock mass) were monitored and shown in Fig. 9, compared to the outside air temperature. The measurements show that the frost insulated drain can even out the temperature changes that occur in the tunnel air directly adjacent to the drain, but that the temperature behind the drain drops slowly below zero degrees at the end of both winter periods.

Insulated drain mats does not only prevent the cold air from reaching the leakage spots, it also prevents the rock mass from emitting geothermal heat that warms up the tunnel air. Consequently, the freezing temperatures penetrate further into the tunnel than they would if the heat from the rock mass was allowed to warm up the outside air on its way into the tunnel (Andrén, 2009). Therefore, ice problems arise further in along the tunnel (Andrén, 2008).

There is a discrepancy between the temperatures and the frost penetration obtained from the field measurements and the laboratory model test (Sandberg et al., 2002). This discrepancy may be due to the difference between the behaviour of the real tunnel and the assumptions used in the model tests. The laboratory model tests assumed a completely uninsulated tunnel, while the Glödsberg tunnel has a large number of insulated drain mats. However, since the lower northern third of the Glödsberg tunnel only has 2% coverage of insulated drains, the conditions of thermal exchange between rock and air in this section are considered to be comparable to the conditions simulated in the laboratory model test. According to the laboratory model test, the frost penetration should only reach about 540 m from the lower northern tunnel entrance at an outside temperature of -15 °C (see Fig. 8). But according to the field measurement, the tunnel air temperature at 540 m from the lower northern tunnel entrance is about -7 °C (see dotted line in Fig. 6). The charts from Sandberg's model test seem to overestimate the temperature in the tunnels and the model is not directly relevant for insulated or partially insulated tunnels. The frost penetrates much further into the tunnel and in the case of the Glödsberg tunnel, throughout the whole tunnel length. To evaluate the frost penetration,

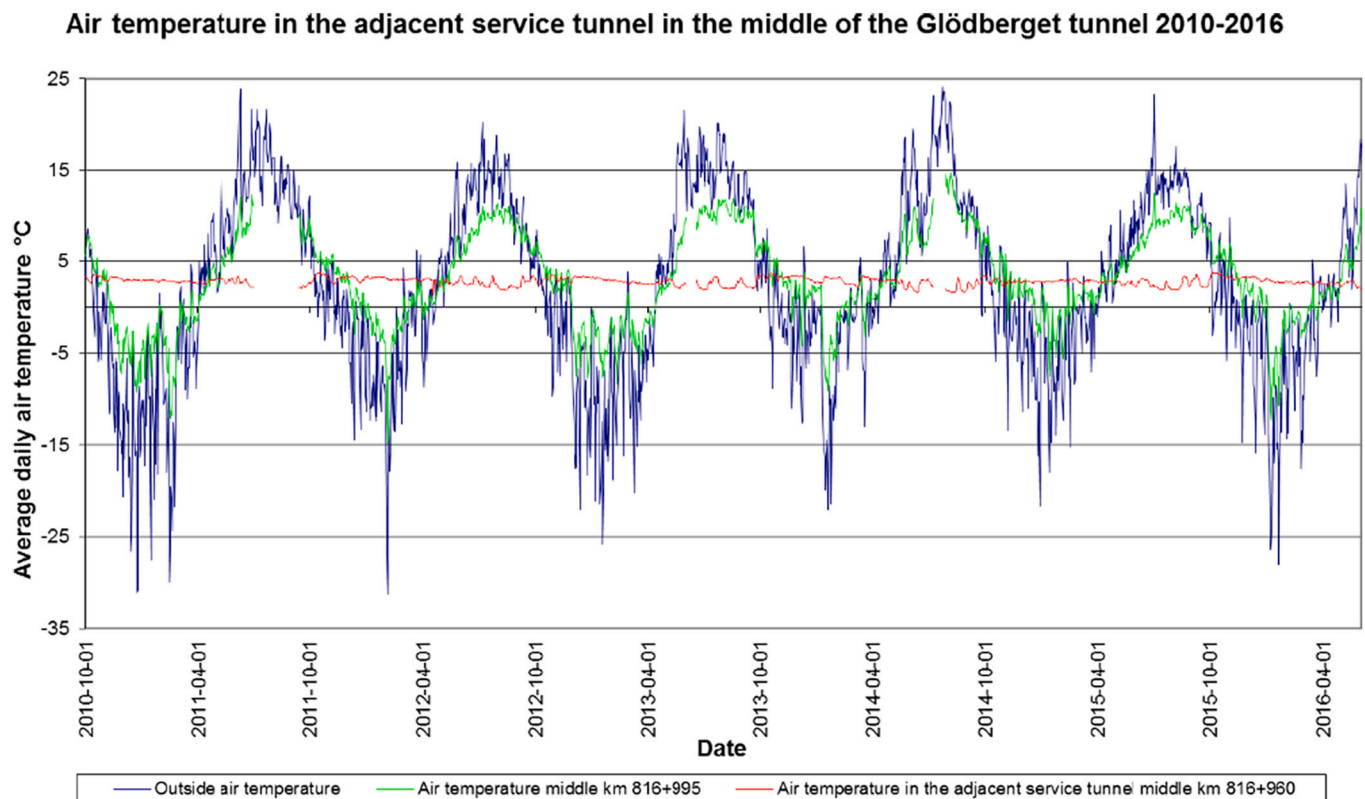


Fig. 11. Temperature in the adjacent service tunnel (Glödsberg 2010–2016).

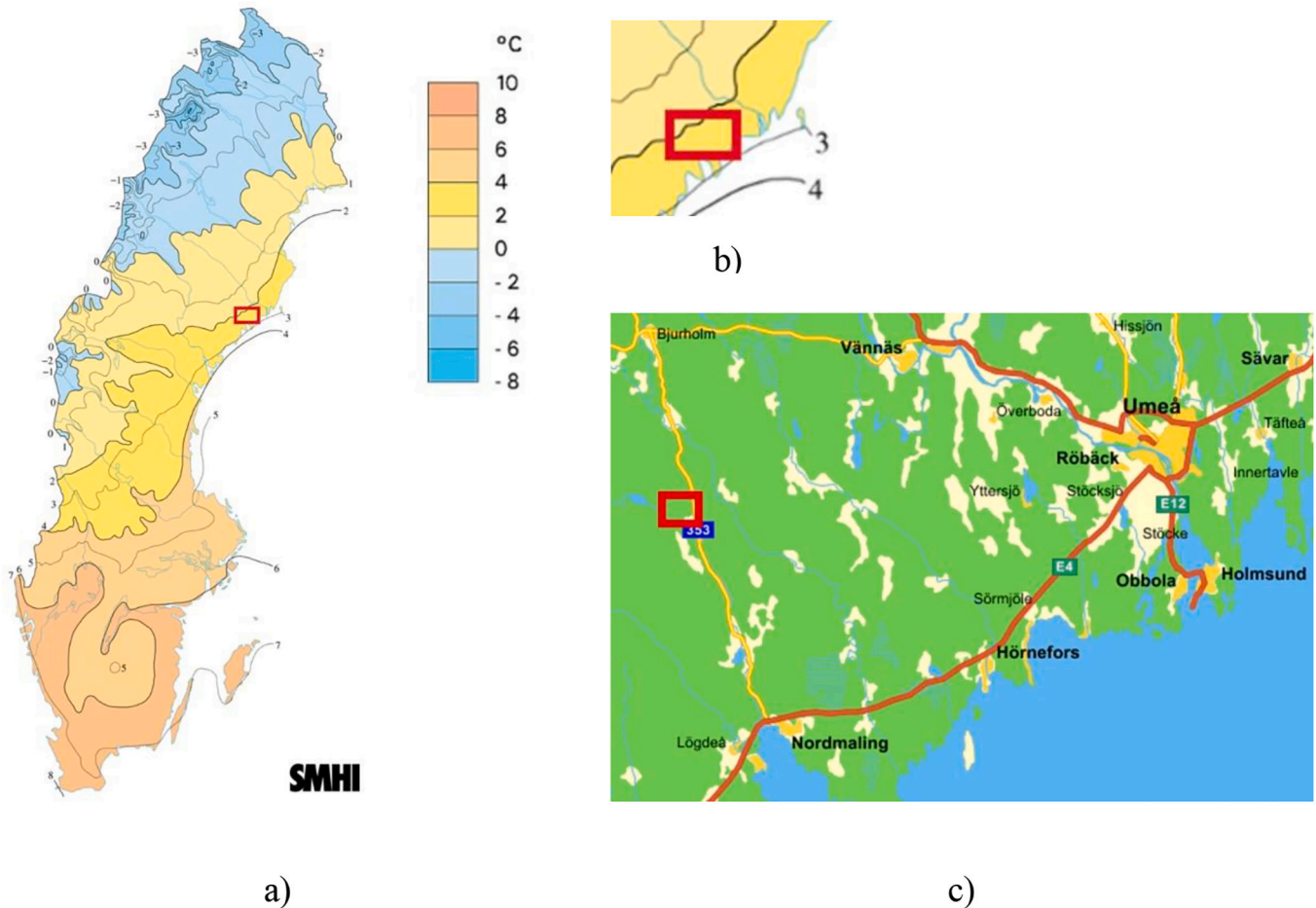


Fig. 12. a) The annual average temperature in Sweden – the location of the Glöddberget tunnel is marked with a red rectangle (modified from SMHI) b) Close-up – the location of the Glöddberget tunnel is marked with a red rectangle (modified from SMHI) c) Map with the location of the Glöddberget tunnel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

consideration must be given to how much of the walls and roof are covered with insulation and how the insulation is distributed along the tunnel.

3.3. Impact of air movements in the tunnel

To improve knowledge about air movements in track tunnels, gauges for air velocity were installed in three sections along the Glöddberget tunnel (see Fig. 4). The wind direction and velocity outside the tunnel, needed for comparison, were registered at a meteorological station outside the southern entrance of the tunnel. Measurements made by and presented by Andrén et al. (2020) and Andrén, (2008–2016) are shown in Fig. 10. The measurements show that during the winter periods, when the temperature difference between the outdoor air and the tunnel air (heated by the rock mass) is greatest, the air movements increase over the entire length of the tunnel. This is indicated by an increased air velocity at the middle measurement station (green curve) for these periods. During the rest of the year, the air velocity at the middle measurement station is lower than at both the higher southern (pink curve) and the lower northern measurement station (cyan curve).

To find out how air movements affect the tunnel air temperature,

measurements were also made in the adjacent service tunnel. The airflow in the service tunnel is constrained, as opposed to the air motion in the track tunnel, because the service tunnel has closed doors both towards the track tunnel and to the outside air. The entrance to the service tunnel is located in the middle of the track tunnel, at chainage km 816 + 960. Measurements reported in Andrén et al. (2020) and Andrén, (2008–2016) show that the air temperature is almost constant throughout the year, around 2–3 °C regardless of the temperature outside the tunnel, see Fig. 11 (red curve = air temperature in the adjacent service tunnel, green curve = air temperature in the track tunnel right next to the service tunnel door, blue curve = air temperature outside the tunnel).

The measured air temperature in the service tunnel corresponds to the normal temperature of the rock mass, which usually coincides with the annual average temperature (Erlström et al., 2016) that applies to the region where the tunnel is located. The annual average temperatures, according to SMHI (SMHI – the Swedish Meteorological and Hydrological Institute, n.d.) are given in Fig. 12 and the temperature at the location of the Glöddberget tunnel is about 2–3 °C (red rectangle).

Airflow resulting from the chimney effect in a tunnel has a major impact on the frost penetration. Sandberg et al. (2002) reported air

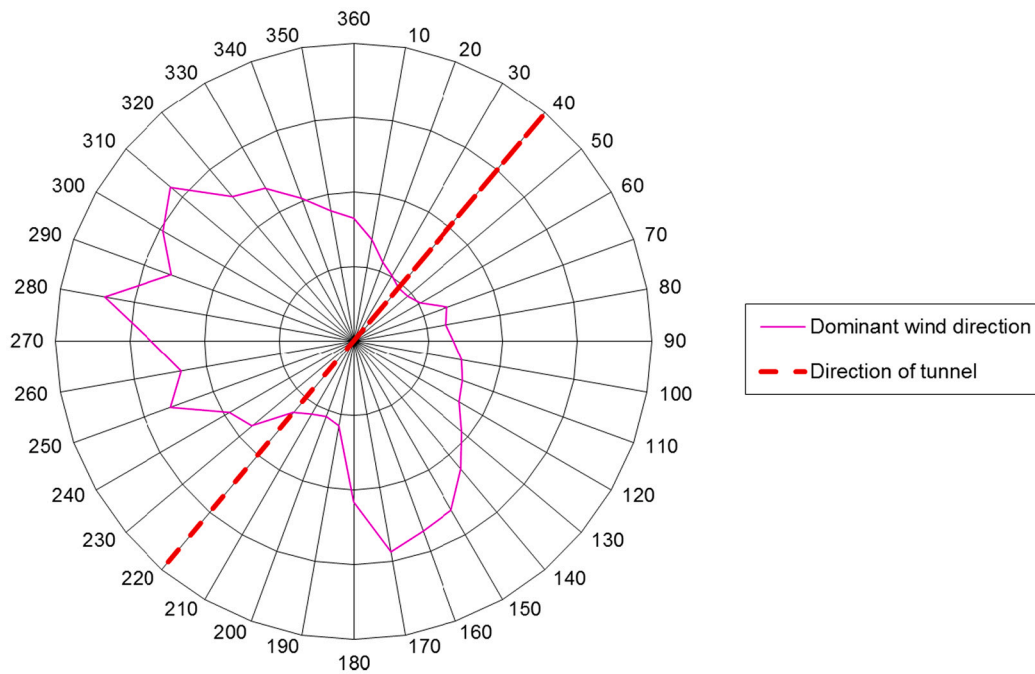


Fig. 13. Dominant wind directions at the Glödsberg tunnel 2007–2010 and direction of tunnel.

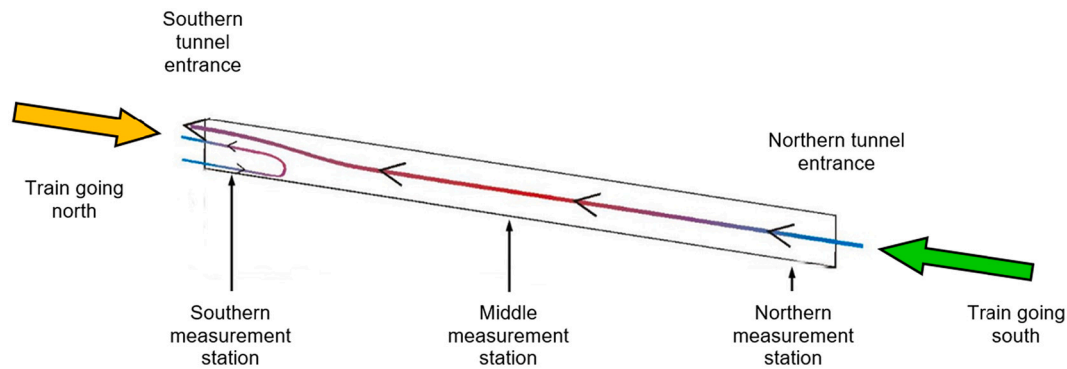


Fig. 14. Location of the measurement stations in the Glödsberg tunnel and direction of train passage (background picture modified from Sandberg et al., 2002).

Table 1

Train passages through the Glödsberg tunnel 2017–11–21.

Time	Train No	Type of train	Direction	Weight (ton)	Length (m)
12:10	41904	Freight	Going north	1054	481
12:20	4590	Freight	Going north	878	513
12:52	4051	Freight	Going south	–	–
13:13	41431	Freight	Going south	2221	502

velocities in tunnels due to different tunnel lengths, slopes and the temperature difference between the air inside and outside the tunnel. In a tunnel with similar conditions to the Glödsberg tunnel (10‰ inclination, $\Delta T = 16^\circ \text{C}$, length 1700 m), the reported air velocity is about 1–1.2 m/s. This is similar to the measured air velocity, which is between 0.5 and 1.5 m/s in the Glödsberg tunnel (pink, green and cyan curves in Fig. 10).

3.4. Impact of outside wind

Measurements made by Andrén et al. (2020) and Andrén, (2008–2016) showed that the dominant wind direction at the Glödsberg tunnel differs from that of the tunnel entrances (Fig. 13), and therefore the outside wind does not significantly affect the air movements in the tunnel. In Fig. 10 the southern and northern measuring stations are sometimes, when the wind direction is the same as the direction of the tunnel, slightly affected by the outside wind velocity (peaks follow each other). But the air velocity in the tunnel is not of the same magnitude as the outside wind velocity. For more information, the following publications are recommended: Andrén et al. (2020) and Andrén, (2008–2016).

According to Sandberg et al. (2002), a typical average wind velocity 10 m above the ground level during winter in Sweden is about 3–4 m/s. This corresponds closely to the measured value of wind velocity outside the tunnel (black curve in Fig. 10). The estimated effective wind velocity at the level of the tunnel entrance is, according to Sandberg et al. (2002), about 2 m/s. If the distance between the tunnel entrances is large, local

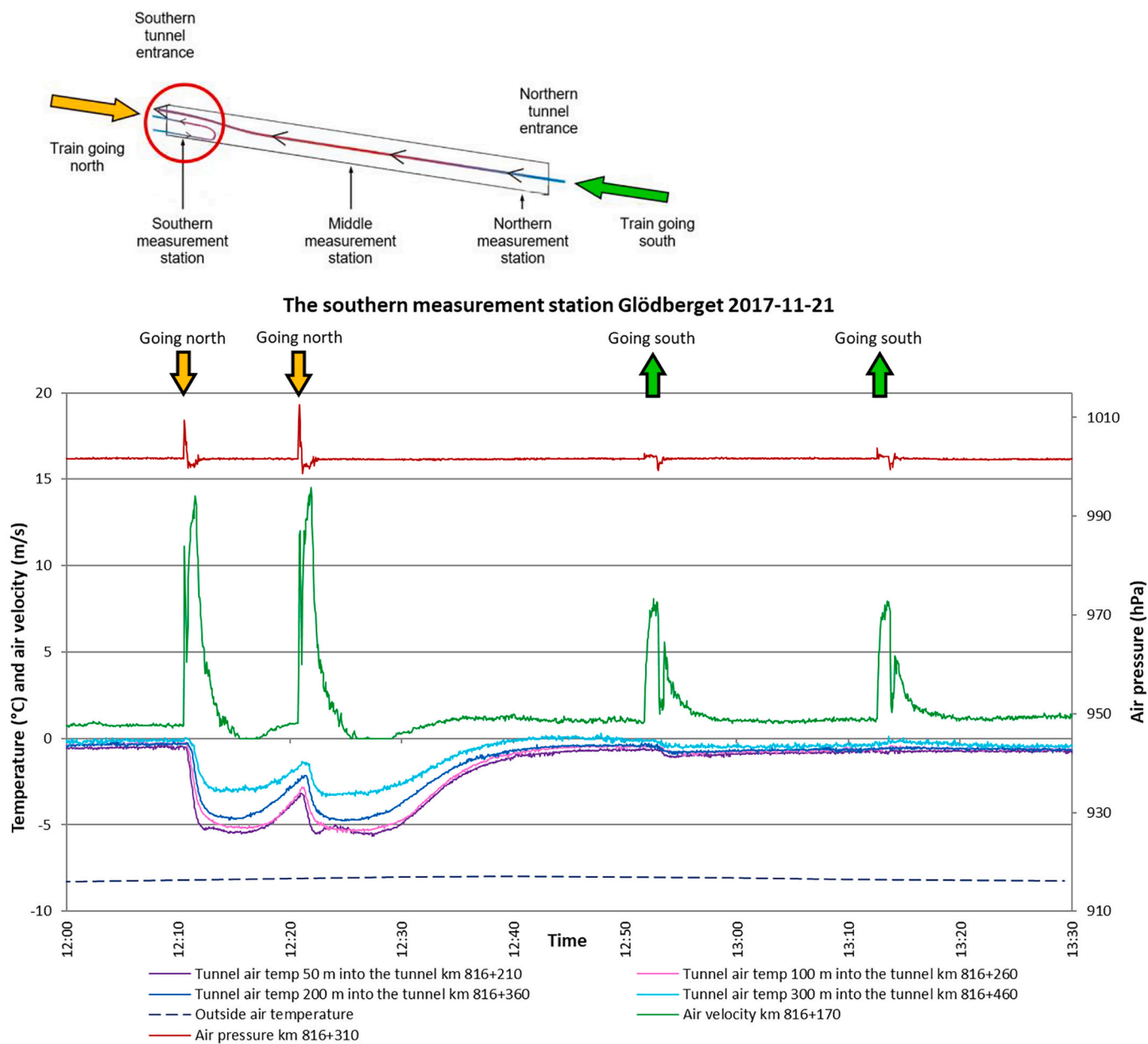


Fig. 15. Four train passages through the Glödborget tunnel 2017-11-21, the southern measurement station.

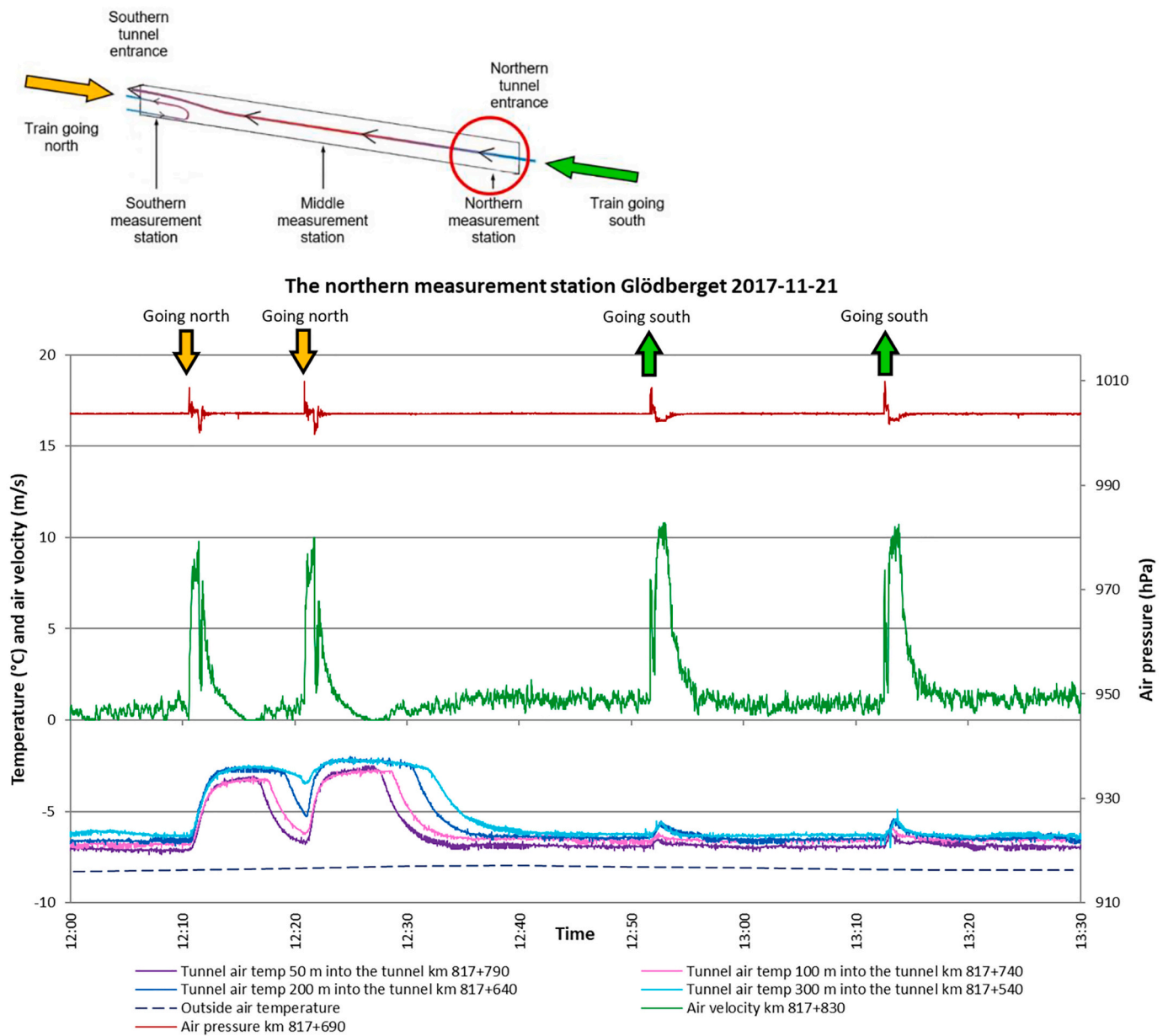
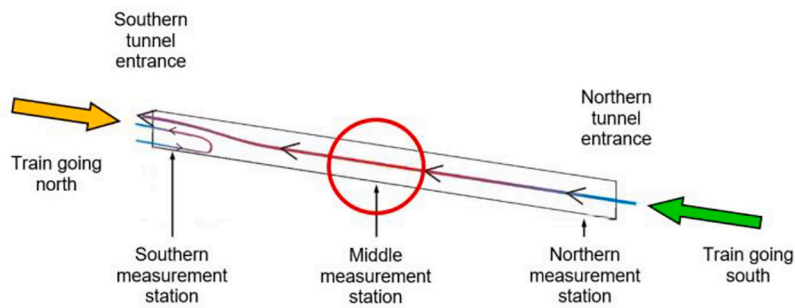


Fig. 16. Four train passages through the Glöddberget tunnel 2017-11-21, the northern measurement station.



The middle measurement station Glödsberget 2017-11-21

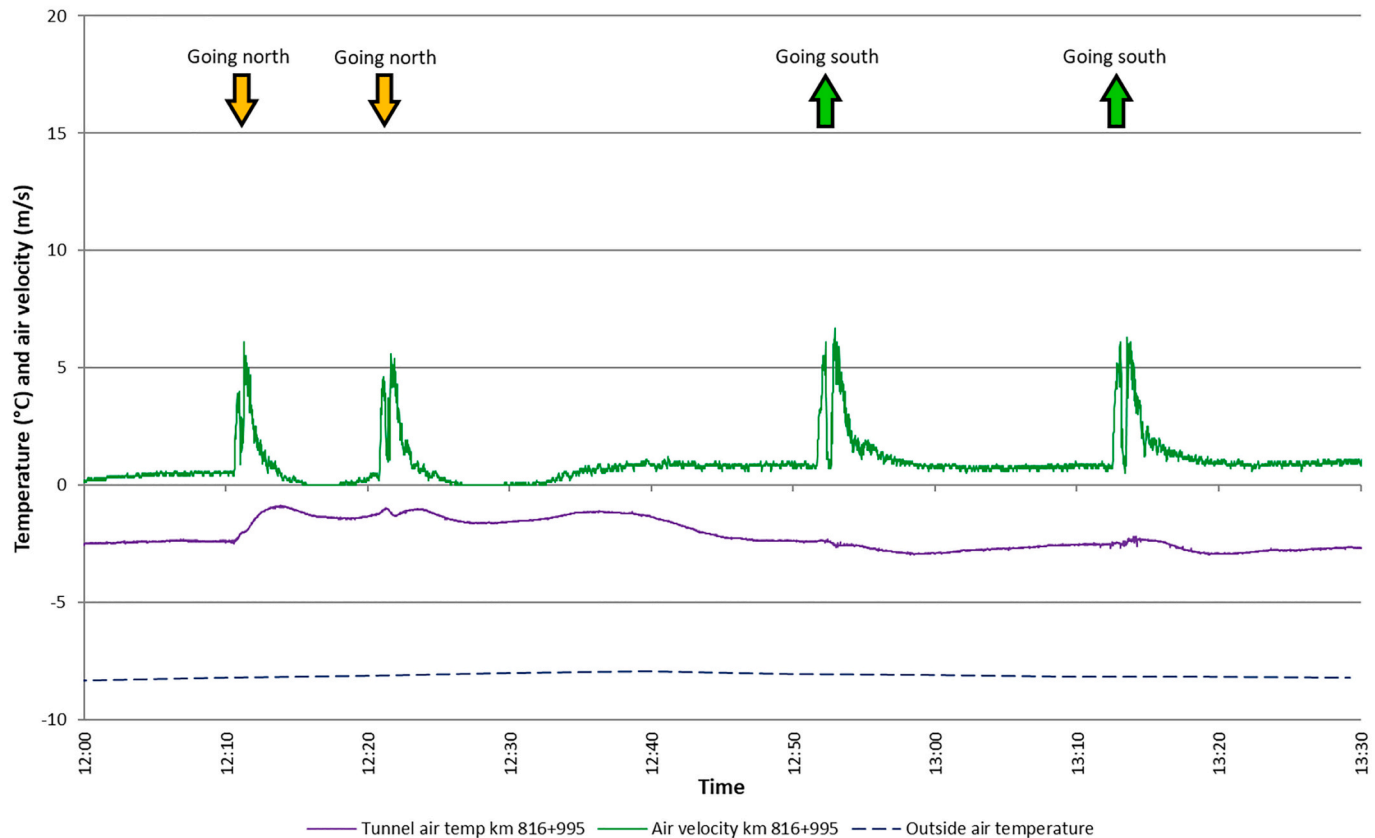


Fig. 17. Four train passages through the Glödsberget tunnel 2017-11-21, the middle measurement station.

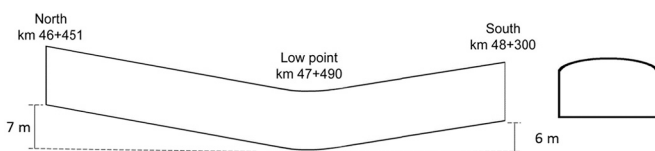


Fig. 18. Longitudinal sketch of the Åsa tunnel (not to scale).

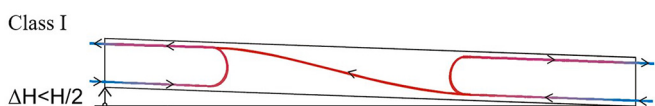


Fig. 19. Airflow pattern for Class I (modified from Sandberg et al., 2002).

variations in the wind conditions can be expected, for example, completely different wind directions at the two tunnel entrances. In windy conditions, the air velocity in the tunnel can reach up to between 20 and 40% of the wind velocity outside the tunnel, but the effect of the outside wind is usually not long-lasting. Since the dominant wind direction at the Glödsberget tunnel according to Fig. 13 does not coincide with the direction of the tunnel, no conclusions about the impact of the wind could be drawn in this field survey.

3.5. Impact of train passages

When trains pass through the tunnel, the air is set in motion. The laboratory model test (Sandberg et al., 2002) showed that the magnitude of the created air velocities in the tunnel is directly proportional to the train velocity. The train sets create high air velocities in the tunnel, up to 20–30% of the train velocity, but after the train passage, the air velocity decreases due to friction against the tunnel walls. The air velocity decreases fast and after less than 1 min the effect from the train passage has

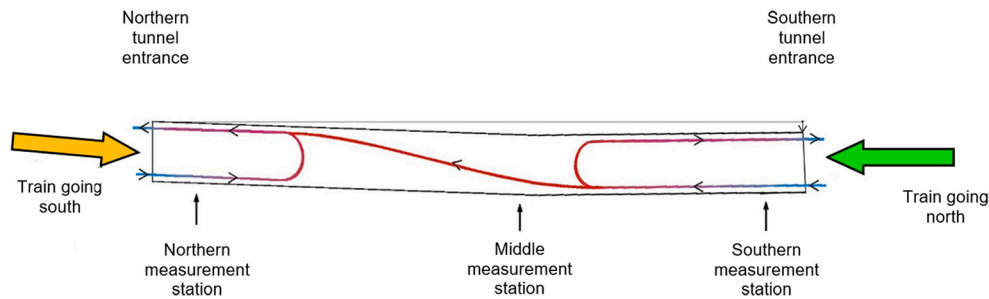


Fig. 20. Location of the measurement stations in the Åsa tunnel and direction of train passage (background picture modified from Sandberg et al., 2002).

Table 2

Train passages through the Åsa tunnel 2012-01-31.

Time	Train No	Type of train	Direction	Weight (ton)	Length (m)	Speed (km/h)
10:08	1057	Passenger	Going south	306	158	180
10:21	485	Passenger	Going south	276	115	200
10:47	1020	Passenger	Going north	306	158	180
11:13	1063	Passenger	Going south	306	158	180
11:18	30738	Freight	Going north	324	264	90
11:22	307	Passenger	Going south	170	79	180

vanished. Sandberg et al. (2002) came to the conclusion that train passages had no major impact on the total frost penetration. To evaluate this conclusion, measurements have been made in both the Glödsberg and the Åsa tunnels. The Glödsberg tunnel, with its constant inclination and relatively few train passages per hour, has similar conditions as in Sandberg's model test. The Åsa tunnel is somewhat more complex, due to its low point and also the larger number of train passages. Despite this, the results from the Åsa tunnel are also presented in this article, to highlight any differences. For the measurement stations located in the track tunnels, a program loop can be manually activated, which logs values every 1 to 3 s. These measurements are used to study what occurs in the tunnel air when a train passes through the tunnel. The values stored are air temperature, air velocity and air pressure. A number of measurements have been taken and, because the pattern repeats itself, only one measurement per tunnel is reported in this article.

3.5.1. Measurement when trains pass through the Glödsberg tunnel

Fig. 14 shows the approximate location of the measurement stations in the Glödsberg tunnel and the direction of train passage in the tunnel for northbound (going north) and southbound (going south) trains respectively.

For the Glödsberg tunnel, the measurement series from 2017 to 2021 were chosen. During the measurement series, four trains passed through the tunnel, see Table 1.

Outside the tunnel the air temperature is about -8°C and, at the higher southern measurement station (Fig. 15), the tunnel air temperature is about -1°C at the time of measurement. The temperature decreases when the northbound trains pass, while for the southbound trains there is almost no change in temperature at all. The reason for the temperature drop when the northbound trains pass, is that the trains push cold outside air in front of them which also creates a negative pressure behind the train that draws cold air into the tunnel. For the southbound trains, the cold outside air gets mixed with the warmer

tunnel air along the entire tunnel length. So, when the trains pass the southern measurement station the temperature differences have evened out.

At the lower northern measurement station (Fig. 16), the tunnel air temperature is about -7°C at the time of measurement. The temperature is increased by train passage, especially for the northbound trains. This is due to the fact that the warm tunnel air in the southern part of the tunnel is pushed in front of the northbound trains, thus temporarily increasing the temperature in the northern parts of the tunnel. For the southbound trains, there is a slight increase in the temperature, because the warmer air in the tunnel roof is mixed with the cold air from the tunnel floor during the train passage.

There is also an increase in the air temperature at the middle measurement station (Fig. 17), but it is not as significant as at the northern measurement station (Fig. 16). The warm and the cold tunnel air are mixed by the train passages and the measurements show a slightly higher temperature when the trains are going north, than when they pass southward.

Fig. 15 to Fig. 17 clearly shows that the tunnel air temperature returns to its original temperature relatively quickly after the trains have passed, as suggested by Sandberg et al. (2002). The air velocity shows a similar behaviour.

3.5.2. Measurement when trains pass through the Åsa tunnel

The Åsa tunnel is a double-track tunnel with a length of 1850 m. The elevation difference between the higher north and the lower south entrance is only about 1 m, but the low point further into the tunnel (1039 m in the tunnel from north) is approximately 7 m lower than the northern entrance and 6 m lower than the southern entrance (Fig. 18). The tunnel height is 7.3 m above the top of rail and the width is 14 m.

The Åsa tunnel differs from Glödsberg since it has a low point causing the airflow to differ from the laboratory model test. Fig. 19 shows the result from the model test for the tunnel category Class I (ΔH

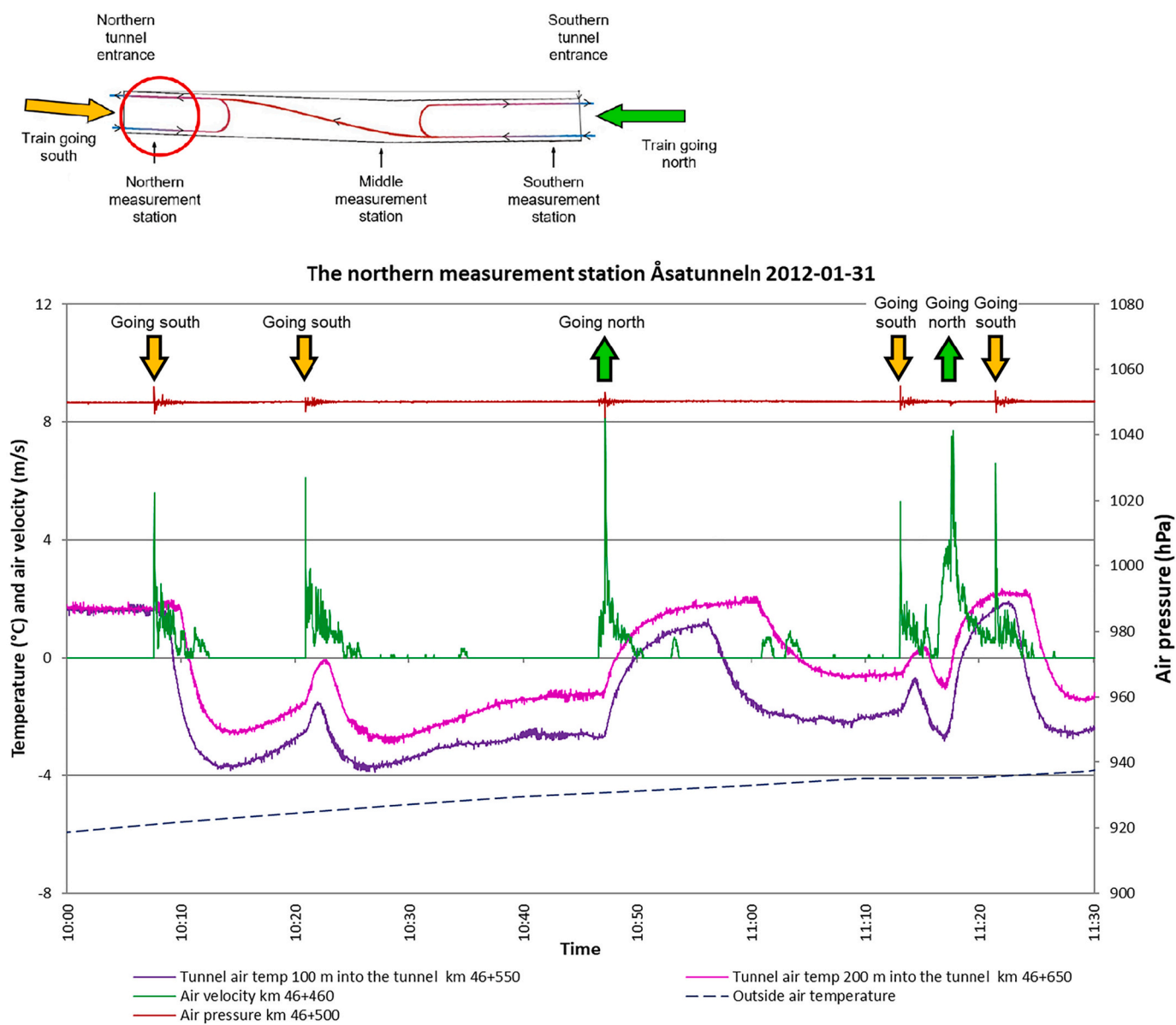


Fig. 21. Six train passages through the Åsa tunnel 2012-01-31, the northern measurement station.

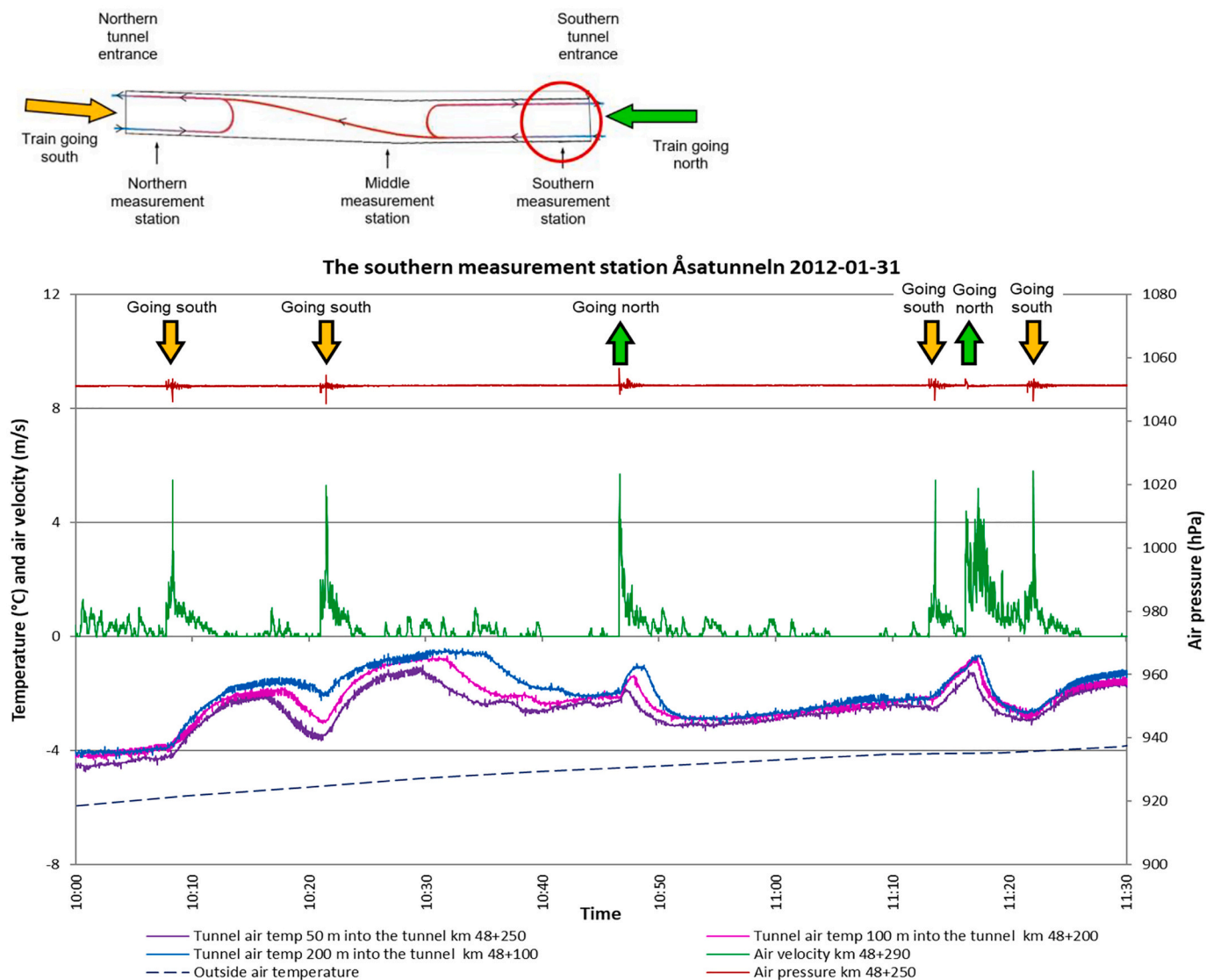


Fig. 22. Six train passages through the Åsa tunnel 2012-01-31, the southern measurement station.

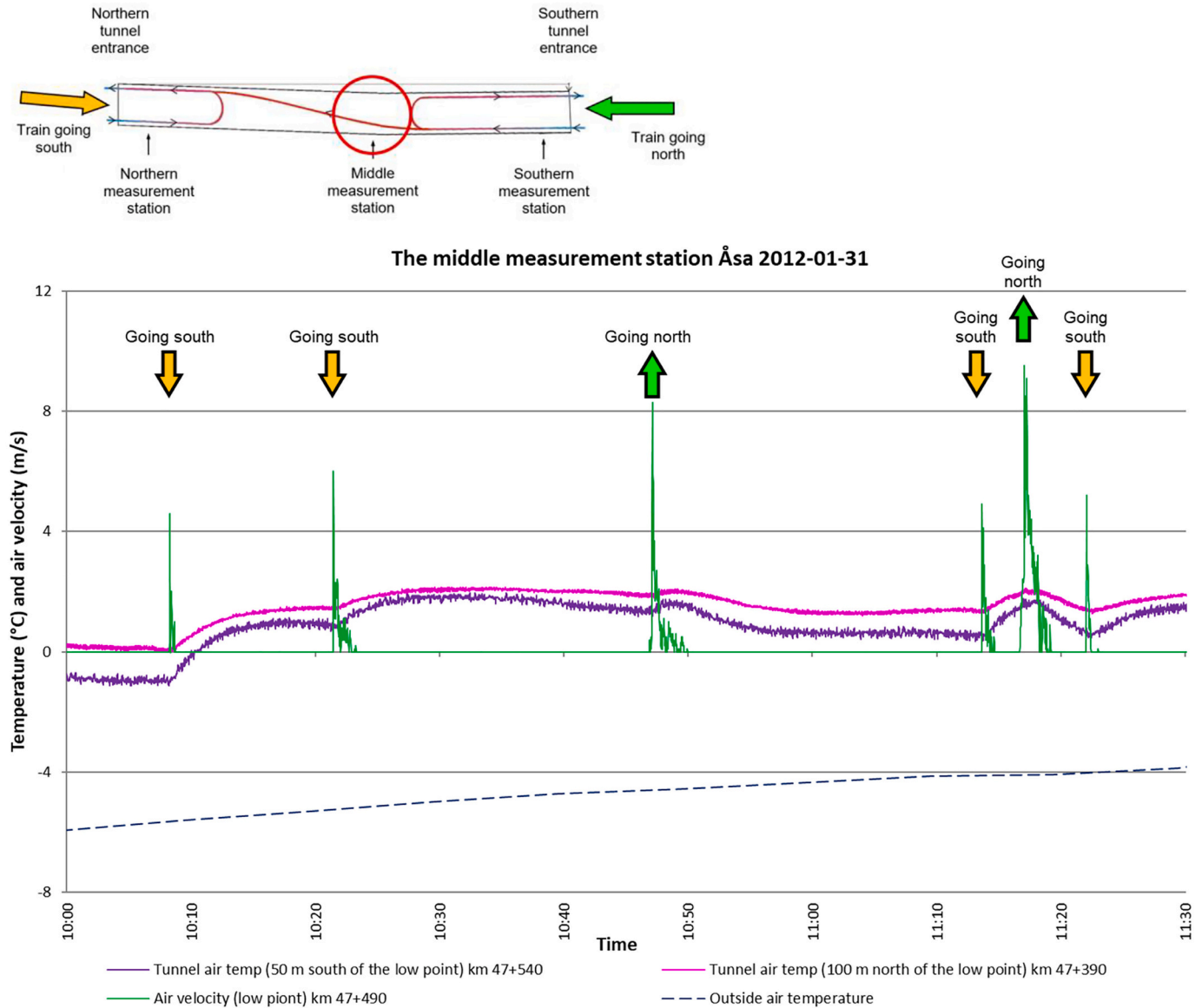


Fig. 23. Six train passages through the Åsa tunnel 2012-01-31, the middle measurement station.

$< H/2$). This category corresponds most closely with the situation in the Åsa tunnel, where $\Delta H = 1$ m and $H = 7.3$ m. Air flows in one direction in most parts of the tunnel and the heated tunnel air rises to the higher entrance. At both entrances, cold air is entering the tunnel along the tunnel floor. When the air is heated, the air direction changes and warm air rises towards the nearest entrance (Sandberg et al., 2002).

Location of the measurement stations and direction of train passage in the Åsa tunnel are shown in Fig. 20. The most suitable airflow pattern from the model test is used in the background.

For the Åsa tunnel, the measurements from 2012 to 01-31 are chosen. During the measurement series, six trains passed through the tunnel, see Table 2.

Outside the tunnel, the air temperature was about -6 °C to -4 °C and, at the higher northern measurement station (Fig. 21), the tunnel air temperature was about 2 °C at the time of measurement. The temperature decreases when the southbound trains pass, while for the northbound trains the temperature increases. The reason for the temperature drop is the same as for the Glödsberg tunnel. The southbound trains push cold outside air in front of them and also create a negative pressure that draws cold air into the tunnel. For the northbound trains, the cold outside air is mixed with the warmer tunnel air along the entire tunnel

length, therefore, the temperature increases when the trains pass the northern measurement station.

At the lower southern measurement station (Fig. 22), the tunnel air temperature is about -4 °C to -2 °C at the time of measurement. The temperature increases when the southbound trains pass, pushing warm air from the northern and inner parts of the tunnel to the southern part. For the northbound trains, the temperature situation is more complex. A smaller temperature increase occurs at first for the passenger train at 10:47, then the temperature drops again. For the freight train at 11:18, there is a temperature drop. The small temperature increase that occurs may be due to the warmer tunnel air at roof level being mixed with the colder air from the tunnel floor when the northbound trains pass, while the temperature drop is due to the fact that the trains draw cold outside air into the southern tunnel entrance.

At the middle measurement station (Fig. 23), the tunnel air temperature is about 0 °C at the time of measurement. There is an increase of the tunnel air temperature for the southbound trains. For the northbound trains, the same situation as for the southern measurement station occurs. First, a small temperature increase occurs when the warm tunnel air is mixed, then a temperature drop due to cold outside air being drawn into the middle of the tunnel.

Fig. 21 to Fig. 23 shows that the tunnel air temperature and air velocity returns to its original values relatively quickly after the trains have passed, as described by Sandberg et al. (2002). In the Åsa tunnel, the tunnel air temperature increases during the measurement series but, as seen in Fig. 21 to Fig. 23, the outside air temperature also increases during this time, so the temperature increase is not due to the train passages.

4. Conclusions

The conclusions from this study are:

- The measurements in the Glödsberget tunnel show that the frost penetrates further into the tunnel than was expected from the laboratory model test, which was based on a completely uninsulated tunnel. The results from Sandberg's model test seem to overestimate the temperature in tunnels with frost insulation and the model is not directly relevant for insulated or partially insulated tunnels. The number of frost insulated drains and how much of the tunnel walls and roof are covered by insulation, thereby affect the length of the frost penetration.
- Frost insulated drains do not only prevent the cold air from reaching the rock mass, but also prevent the rock from emitting geothermal heat that warms up the cold tunnel air. Consequently, the frost penetrates further into the tunnel than it would do if the heat from the rock mass was allowed to warm up the outside air on its way into the tunnel.
- Airflow resulting from the chimney effect in a tunnel has a major impact on the frost penetration. According to the laboratory model test, the air velocity in a tunnel is dependent on tunnel inclination, temperature differences between the rock and the outside air and the length of the tunnel. The laboratory model test reports that the air velocity in a tunnel with similar conditions as the Glödsberget tunnel is about 1–1.2 m/s. This is consistent with the measured air velocity in the Glödsberget tunnel, which varies between 0.5 and 1.5 m/s.
- When the cold outside air is able to penetrate further into a tunnel, the frost problems in the inner sections of the tunnel will increase. Ice problems often occur along the entire length of the tunnel and not only around the entrances.
- Frost insulated drain mats are able to smooth out the temperature changes that occur in the tunnel air. If the temperature is negative for a longer period, the temperature behind drains can drop below zero degrees. Then the water from the rock mass cannot be drained properly and frost shattering or formation of ice pillars and icicles may develop.
- Measurement in the adjacent service tunnel shows that airflow in the track tunnel has a major impact on the frost penetration. The airflow in the service tunnel is constrained, because it has closed doors both towards the track tunnel and to the outside air. The air is heated by heat exchange between the rock mass and the air, and the tunnel air adopts the same temperature as the surrounding rock mass. This temperature usually coincides with the average annual temperature of the region where the tunnel is located.
- According to the laboratory model test, the air velocity in the tunnels can reach up to between 20 and 40% of the wind velocity outside the tunnel in very windy conditions, but the effect of the outside wind is usually not long-lasting. Since the dominant wind direction at the Glödsberget tunnel does not coincide with the direction of the tunnel,

no conclusions about the impact of the wind could be drawn in this field survey.

- The impact of train passages on frost penetration is that the tunnel air is set in motion and the trains create very high air velocities in the tunnel. The laboratory model test and the performed field measurement showed consistent results. The air velocity reduces quickly after the passage and the conclusion is that train passages have no greater impact on the total frost penetration.
- The field measurements show that the temperature increases or decreases due to train passages depending on where in the tunnel the measurement takes place and which direction the train runs in the tunnel. When measuring in the higher, warmer part of an inclined tunnel, the temperature decreases when trains enter the tunnel in this part, because cold outside air is pushed and drawn into the tunnel by the train. When the same train moves downwards in the tunnel, it creates a temperature increase at the lower, colder part of the tunnel since the train pushes warmer air in front of it, on its way through the tunnel.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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