

THERMAL MONITORING OF MOTORWAY TUNNEL INSULATION STRUCTURES

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ABSTRACT

In road tunnels in Finland, water and frost isolation lining is needed to ensure traffic safety due to the ground water leakage and freezing problem during winter time. Insulation also improves the stability of the rock mass around tunnels, since freezing - thawing phenomena can be avoided. Adequate and well positioned lining diminishes maintenance costs of the tunnel, since formation of icicles is avoided and roads do not become slippery due to frozen water drops.

Typical lining consists of polyethylene sheets covered with shotcrete as fire protection. The lining is very costly so the dimensioning, both in length and thickness, must be done carefully and case by case. Adequate information of the temperature as well as insulation properties is needed for the dimensioning of the lining.

This paper presents a development study to evaluate functioning of the isolation lining versus dimensioning done during design phase of seven motorway tunnels. The lining structures in the tunnels were thermo-mechanically modelled prior to construction. Based on the continuous temperature measurements in the tunnels and updating of the created model, new and valuable info is gained for next projects. With the new info obtained from this study, both construction and maintenance costs can be limited.

1. INTRODUCTION

In cold climate regions, as in Finland, temperature can be continuously under 0 degree for 4–6 months between November and March and go down to -20°C for weeks. Also, a shallow water table level allows the situation where all the rock tunnels are surrounded by ground water. The combination of the water and frost creates ice (Figure 1) and that leads to a need of sufficiently insulated inner lining structures in tunnels against icing in the tunnel roof and walls.

Especially in road or other transportation tunnels the frosting phenomena need to be handled properly. These phenomena cause extensive safety problems as well as continuous tunnel maintenance during winter time. On the other hand, frost expansion behind tunnel lining reduces the stability of the rock, which with ice forming may cause structural damages of the lining. Further, the drainage system of the road structure may freeze and extended icing can lead to wide damages of road structure if frost protection is insufficient.



Figure 1 - Frozen ground water leakage from a rock joint in a construction phase for motorway tunnel entrance on Highway 1, Finland.

Construction of the lining is very expensive and is to be avoided or limited if possible. The cost of the constructed insulation lining is about 80 € - 120 €/m². So, for example the price for the continuous lining for 2.2 km motorway tunnel with twin tubes is approximately 10 M€. Intensive grouting against the leakages might reduce the need of lining, but that is costly, as well. So, good design for optimization is needed. And if lining is used, the operation and maintenance (O&M) cost should be minimized.

However, the lack of knowledge of the temperature behaviour inside the tunnels, especially behind the structures, and possible influence of frost on structure stability hinders the designers from optimizing the lining. Without adequate control, monitoring measurements or simulation techniques together with comparison with “real life” situation, the optimization of the lining is impossible.

This paper presents a study of knowledge improvement on how winter season with continuous frost affects tunnel lining and O&M costs [1]. A thermal simulation method was used to design the structures in the case project and installed monitoring systems were used to examine thermal behaviour in the tunnels and structures during the operation.

A simulation technique was utilized first to create appropriate design prior to construction. On these simulations, experiences and measurement data from the existing tunnels were used. At the later stage, the same simulation methods were used to analyze measured/monitored temperature results from the tunnels and further to predict how the designed and installed frost protection would perform. Throughout the whole process, freezing index analysis was also varied. It is clear that as to the already constructed tunnels, these results are obtained too late to be utilized for structure selection, but the analyses can be very valuable in the coming traffic tunnel projects. However, another target of the study was to have thermal behaviour information from behind the installed insulation structures, and that information can be utilized as guideline for O&M approach.

All the presented studies, designs and cases are mostly from Highway 1 between Helsinki, the capital of Finland, and Turku. The highway section of 52 km was constructed in 2001–2009 by using the Finnish approach of a life cycle model or better known as PPP (public private partnership). For this motorway, seven twin tunnels, the longest being 2.2 km, were

constructed. The Finnish Road Administration has purchased engineering, construction and maintenance from the service provider, Tieyhtiö Ykköstie Oy (a joint venture between Laing Roads Ltd, Skanska ID Ab and Lemminkäinen Oy), up to 2029.

2. WATER AND FROST INSULATION LINING

In all traffic tunnels lately constructed in Finland, water and frost insulation lining is required due to the quite heavy winter season as well as high ground water table level. In most cases, lining is utilized at the first 100–800 m from the entrance where the roughest freezing phenomena combined with shallow overburden exist. In road tunnels creation of icicles must be prevented.

Typically, local insulated drainages or continuous polyethylene sheet lining are utilized in possible or risky leakage and freezing areas as well as at the tunnel portal areas. Lining is installed with rock bolts or steel bars. Thickness of the continuous PE lining varies from 50 to 100 mm, and it is fire protected with about 80 mm steel reinforced shotcrete. In most cases some 150–250 mm open space between a rock surface and the insulation exists, but it can also be installed directly on the surface of the shotcreted and supported rock wall. However, a lining with open space allows slight freezing behind the lining and creates visually more sophisticated surface in the tunnel (Figures 2, 3 and 5).

In the case project, a combination of intensive grouting together with insulation lining was selected. Insulation was installed in continuous manner for shorter tunnels and 100–300 m at the portal areas for long tunnels. Also, local lining structures with varying lengths were utilized. As seen in Figure 2 & 3, concrete barriers against collision are installed in the lower part of the wall. In the presented Highway 1 case, freely standing 2 m high and 4 m long steel reinforced concrete elements were used. Contact between the lining and element is critical to create air tight conditions behind the lining.



Figure 2 - Typical water and frost insulation lining structure from a Highway 1 motorway tunnel in Finland. Polyethylene sheets are installed with steel bars and steel net, and fire protected with schotcrete. There is minimum 250 mm of empty space behind the lining.



Figure 3 - Ready made interior in a motorway tunnel. Final lighting to be installed.

3. THERMAL MODELLING PRIOR TO CONSTRUCTION

3.1. Base for the simulations

During the design phase of the Highway 1 tunnels in Finland, the insulation structure was dimensioned by using simulation method. Based on the simulation, the need and thickness of the insulation both on the wall and roof lining as well as floor of the tunnel for drainage systems were analyzed. The client's requirement was to have a continuous 100–110 mm thick water and frost insulation lining together with the control and inspection possibilities in the risky areas. All the changes had to be approved by the client. Since the required lining is extremely expensive, another alternative was studied.

The utilized thermal simulation platform is based on Geo-Slope 2D Temp-W software. Thermal simulation needs the following material properties: dry densities, water contents, volumetric heat capacities (frozen/unfrozen), thermal conductivities (frozen/unfrozen) and heat-transfer coefficients between the used materials. Also boundary conditions like initial temperatures of the rock mass, temperatures of tunnel air and heat flux of heating cable are needed. Measured temperature data is always needed to verify the validity of simulation platform.

Different frost protection structures can be tested in a platform with various outdoor temperature records. The freezing index of dimensioning winter has to be changed to the temperatures of the tunnel air in the thermal simulation. The main purpose of the thermal simulation is to determine sufficient frost protection thickness of the lining and drainage environment. All kinds of cold bridges through the frost protection lining must be avoided.

During the operation phase, the temperature measurements together with statistical air temperatures (for example temperatures occurring once in 20 or 50 years) allow determination of thermal behaviour forecasts of frost protection solutions for the rest of the winter by using the same simulation as for the design. Also, this enables the service provider to control risks as well as O&M costs.

3.2. Simulation results

In this study, the thermal modelling was used to evaluate the influence of the magnitude of apparent heat flow on the temperature behaviour of the rock behind the lining. So, in other words, the aim was to evaluate the minimum thickness of the insulation needed to minimize the risk of freezing behind the lining. The model could not take into account the

aerial or air flow conditions behind the lining between rock, but the simulation was based on the apparent heat flow based on the temperature measurement in an existing Pönttövuori railroad tunnel and modelling [2]. The selected freezing indexes were statistically once in 10 years and once in 50 years measured frost amount, being $F_{10} = 27.000 \text{ hours}^\circ\text{C}$ and $F_{50} = 36.000 \text{ hours}^\circ\text{C}$.

The influence of the heating cable was also evaluated for thermal behaviour of the structure (Figure 4). The power of the heating cable was selected to be 60 W/meter of the cable and the cables were planned to be installed at the bottom of the tunnels behind the concrete barriers (one at each side). It was found that two cables at the bottom do not affect the temperature at the highest point of the tunnel, so one similar cable was planned to be installed in the roof of the tunnel. By this technique, the thickness of the insulation could be diminished from 100 mm (requirement from the client) to 70 mm. Difference is not huge in material cost, but installation of thinner lining is much easier due to the fact that 100 mm lining consists of two 50 mm plates.

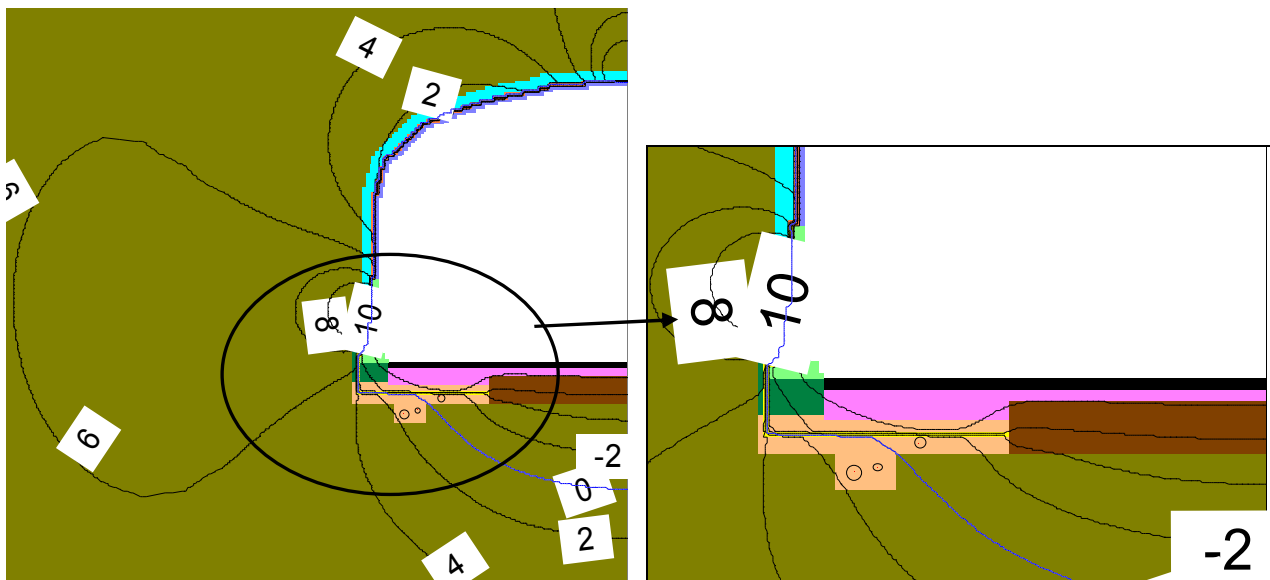


Figure 4 - Example of the simulated temperatures with freezing index F_{50} and heating cables (60 W/m) at both sides of the tunnel behind the collision barrier as well as at the roof. Insulation for wall and roof is 70 mm polyethylene sheet, insulation for concrete barrier and drainages is 70 mm XPS polystyrene sheet.

In both cases the air flow conditions behind the lining create uncertainty in the results even though the planned lining is supposed to be air tight. The main outcome of the simulation and thermal modelling is presented in Table 1.

4. MONITORING SYSTEMS

The Technical Research Centre of Finland, VTT, had an opportunity to develop the thermal monitoring and simulation system during the construction works of the new E18 motorway tunnels in Finland. The developed and instrumented thermal monitoring systems were aimed to manage thermal behaviour of frost protection solutions of the tunnels. Monitoring systems cover wired Pt-100 sensors and data loggers for long-term sensing situated in critical places in frost protection structures in motorway tunnels.

Table 1 - The main conclusions from the thermo mechanical simulation as a design guideline for insulation structures in Highway 1 motorway tunnels in case of F_{10} and F_{50} frost amounts.

Adequate insulation without extra heating	F₁₀ winter	F₅₀ winter
Insulation for the back of the collision barrier:		
Insulation thermal resistance, m_2K/W	1,90	2,43
Insulation thickness for ex. XPS polystyrene sheet, mm	70	90
Insulations of the walls and roof:		
Insulation thermal resistance, m_2K/W	2,00	2,75
Insulation thickness for ex. polyethylene plate/sheet, mm	80	100
Insulation for the ground drainages:		
Insulation thermal resistance, m_2K/W	1,90	2,43
Insulation thickness for ex. XPS polystyrene sheet, mm	70	90
Length/width of the XPS insulation from the collision barrier towards the centreline of the road (connected to barrier insulation)	2,5	2,5
Depth of the insulation from the road surface, m	0,7	0,7
Adequate insulation with heating cable (3 pcs of 60 W/m)		
Insulation for the back of the collision barrier:		
Insulation thermal resistance, m_2K/W	1,35	1,90
Insulation thickness for ex. XPS polystyrene sheet, mm	50	70
Insulations of the walls and roof:		
Insulation thermal resistance, m_2K/W	1,50	2, 00
Insulation thickness for ex. polyethylene plate/sheet, mm	60	80

Thermal monitoring system was composed of wired and mobile sensing solutions with data simulation platform. Basic wired thermal monitoring system consists of RTD sensors, which have been instrumented behind the different thermal insulation structures; drainage systems, collision barrier, single 2 meters and 4 meters wide insulation structure and extended insulated tunnel lining (Figure 5). Also, temperature of the tunnel was measured.

Together with sensor network manufactures two different types of wireless sensor networks were pilot tested to cover mobile thermal monitoring needs in the tunnels. Systems are battery operated and mostly for short-term monitoring in critical places where knowledge of the thermal behaviour and functionality of structures is needed. Both the wired system and two wireless sensor networks, Shinkawa SS1 and SensiNet, were installed in the longest Karnainen tunnel (2.2 km) for comparison between the permanent wired and mobile wireless solutions.

Wireless monitoring has benefits compared to wired solutions; many sensors can freely attach as desired and sensors can be embedded in structures as well, but compared to the wired system, the data transmission up to gateway (Figure 6) is wireless without cabling. Sensors communicate by radio with router or straight with gateway, which is connected over ethernet to computer where data is stored to HDD. SS1 system is fully battery operated and can measure independently many months without PC, because every sensor node has own non-volatile memory and data can be downloaded wirelessly through gateway to PC when needed (Figure 7).

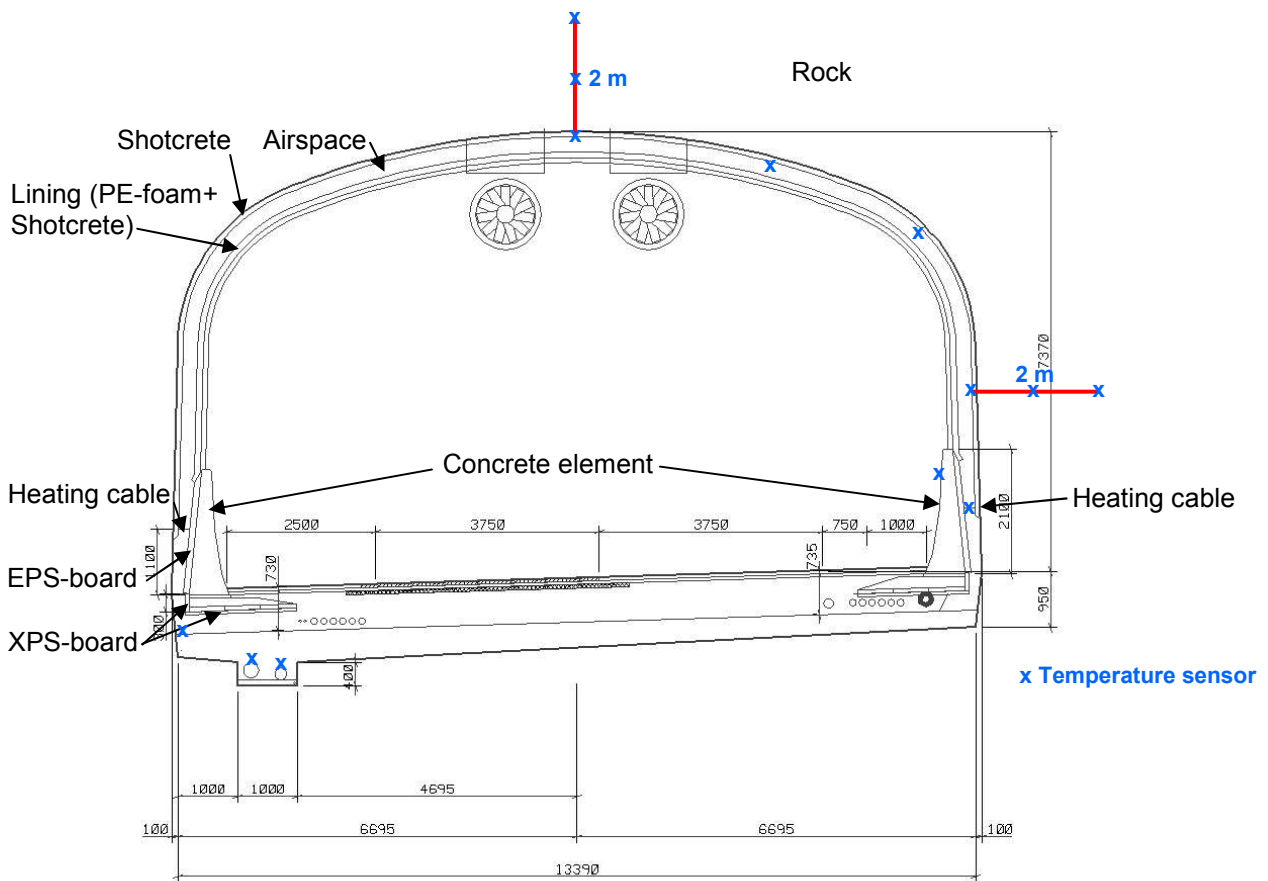


Figure 5 - Typical E18 tunnel cross-section of frost protected lining with instrumented temperature sensors.

Tested sensor networks proved to be workable thermal monitoring systems even in a harsh tunnel surrounding during construction works. Both wired and wireless monitoring systems have remote access via Ethernet, which can be mobilized when optic fibre is ready for use in these tunnels. Nowadays only wired system is in every-day use for monitoring temperatures behind frost protection structures and to lead the usage of heating cables.

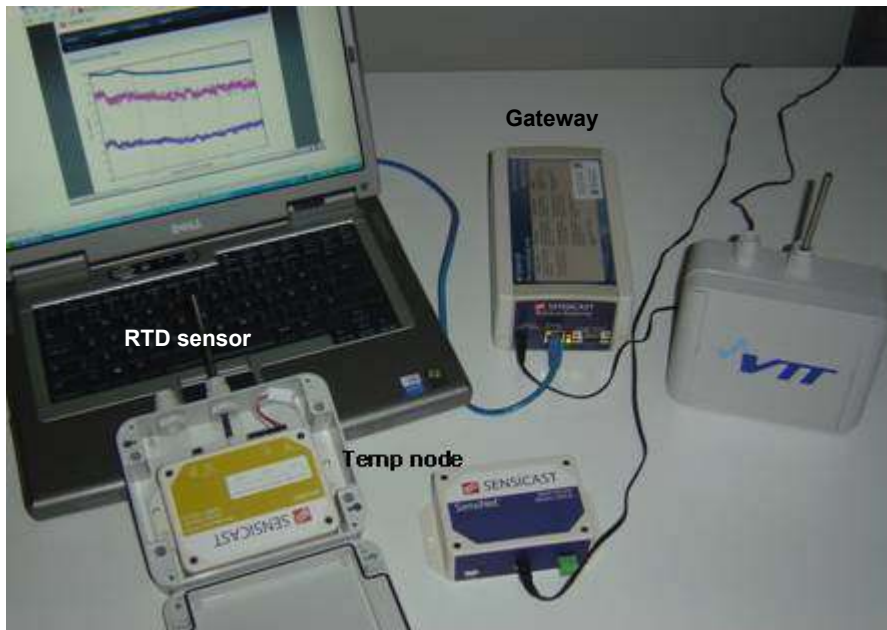


Figure 6 - SensiNet sensor network. System operates with 2,4 GHz radios and radio range is up to 240 meters outdoors.

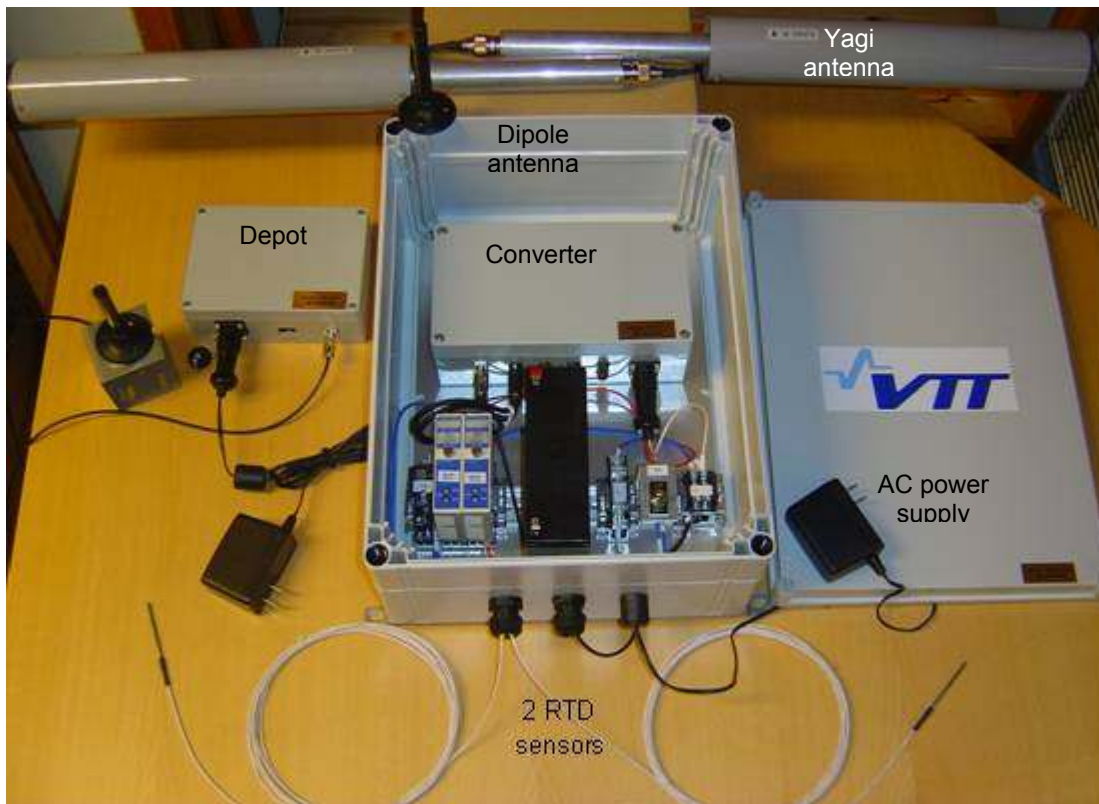


Figure 7 - SS1 sensor network. 2,4 GHz radio and Yagi antennas extend radio range over 300 meters in tunnel.

5. TEMPERATURE MEASUREMENTS IN THE TUNNELS

During the first winter after the opening of the road sections as well the tunnels (2007–2008), the temperature measurement system was tested and found to be working perfectly (Figure 8). However, the winter season was unusually mild, so any concrete evaluations about the performance of the insulations could not be done. Temperature measurements were, anyhow, utilized to confirm the simulation model as well as to control and optimize the need of the heating cable usage and needed heating time.

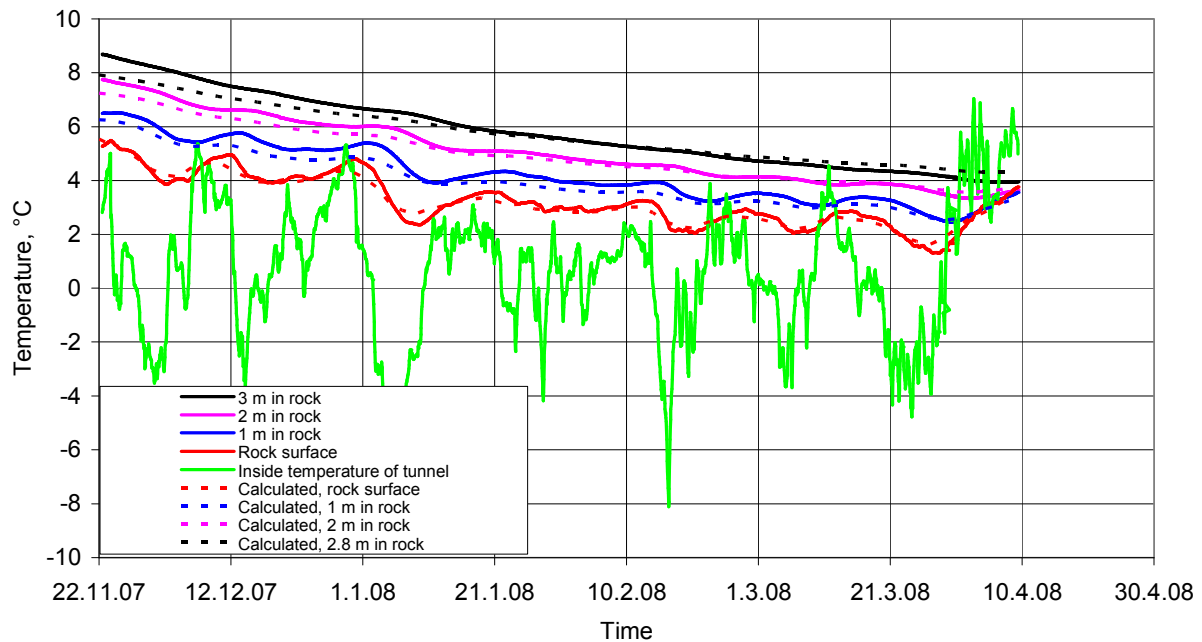


Figure 8 - Measured and calculated temperatures in Lakiamäki road tunnel behind the single (2 m wide) thermal insulation structure during winter 2007–2008 (freezing index was about 1000 h°C).

The winter season 2009–2010 was more “normal”, having rougher freezing conditions. Freezing index was about 19500 h°C during the measurement period. The following figures and graphs (Figures 9–11) present the measured situation in different tunnel locations and measurement points.

It was found that even if the temperature lowered down to -20 °C, the air and rock behind the insulation stayed above 0 °C degrees. So, the designed and installed system was working properly, and frost and ice were not generated. Also, the usage and influence of the heating cable in February 2010 could be controlled by the measurements (Figure 11). The control of heating reduces the operation costs drastically, due to the minimized electrical consumption.

The ongoing winter has been rougher, so it will be exciting to see the outcome.

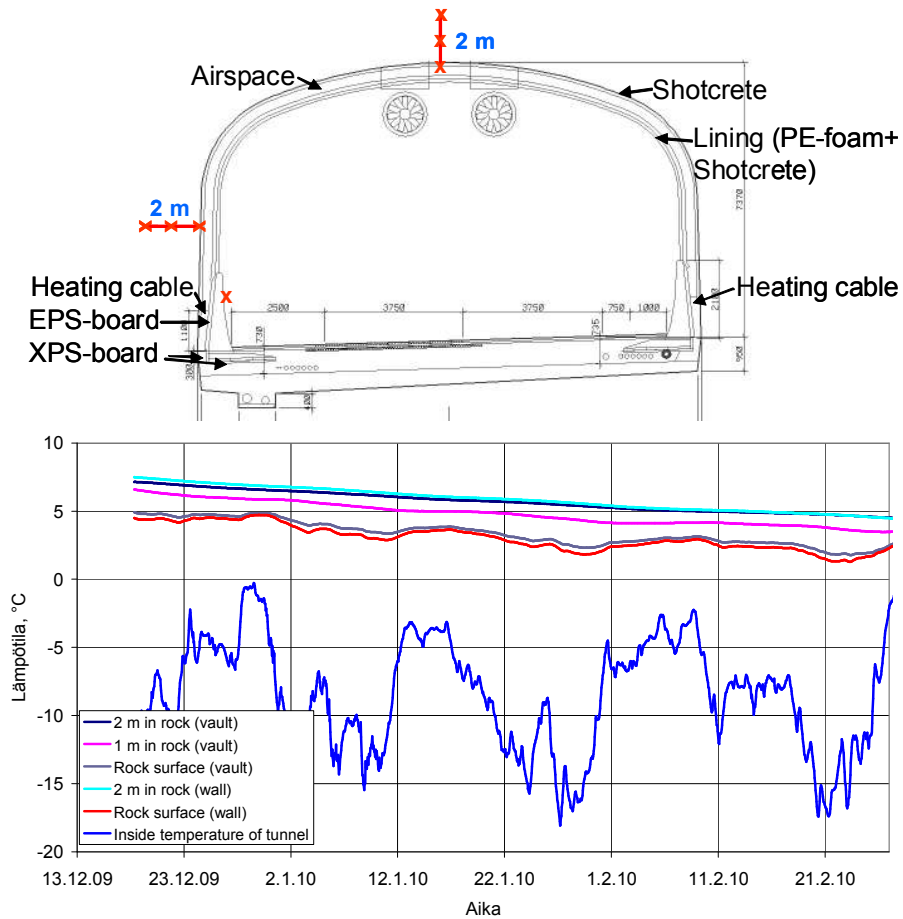


Figure 9 - Measured temperatures in Lakiamäki road tunnel during winter 2009–2010. (Freezing index was about 19500 h°C).

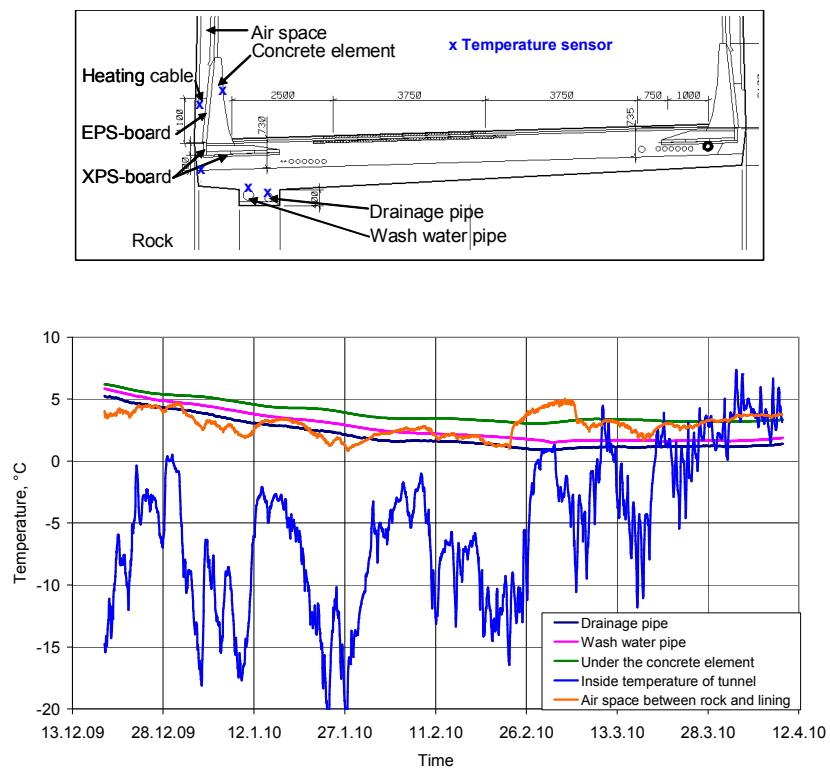


Figure 10 - Measured temperatures in Karnainen road tunnel during winter 2009–2010. (Freezing index was about 19500 h°C).

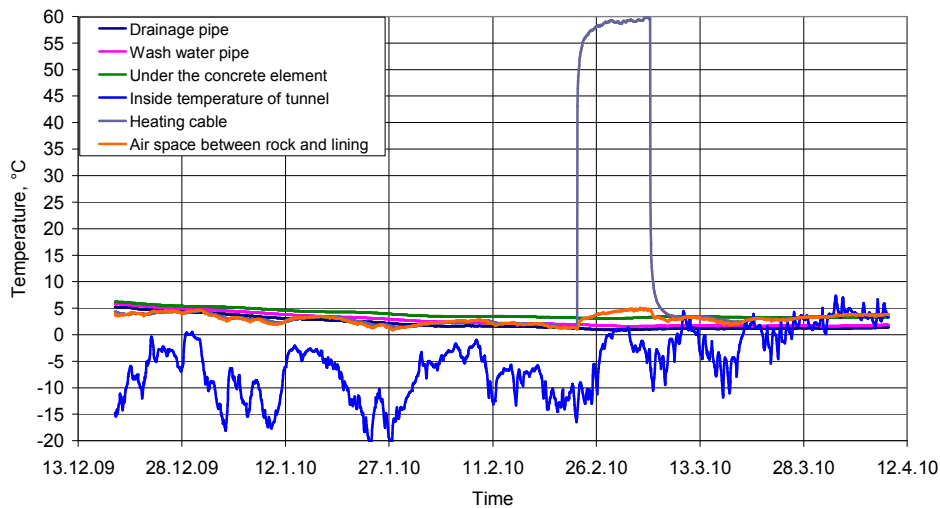
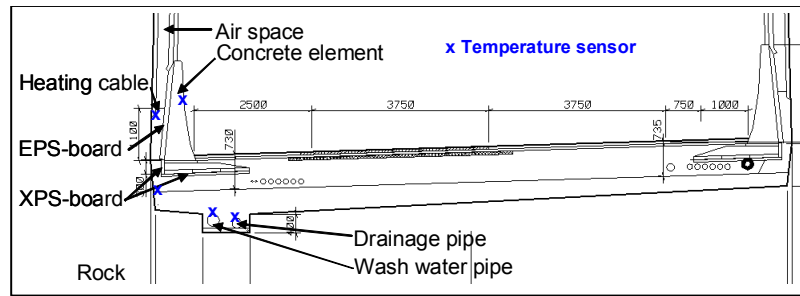


Figure 11 - Measured temperatures in Karnainen road tunnel during winter 2009–2010. (Freezing index was about 19500 h°C). The power switched on in the heating cable for about ten days on 23 February 2010.

6. CONCLUSIONS

The thermal monitoring systems to manage thermal behaviour of frost protection solutions of Highway 1 motorway tunnels in Finland was developed and instrumented. The aim of the system was to gain deeper knowledge of dimensioning parameters of the insulation structures to be able to minimize the costs of the construction as well as O & M costs. The insulation lining is rather expensive but, on the other hand, no icicles or instability of the rock mass due to the freezing – thawing phenomena are allowed to exist in the traffic tunnels.

For the presented case project, Highway 1, rather extensive simulation was applied during the design phase to optimize the lining structure. Also, the thermal monitoring system in the tunnel was successfully implemented. Based on the follow-up thermal measurements, it was found that designed, thinner than required, insulation structures blocked the freezing temperatures digging into the tunnel walls through the lining. If lower temperatures were or will be found in and behind the structures, the installed heating cable network can be turned on and controlled by the measurement system. That has an extensive effect on the O&M costs due to the minimized electrical consumption.

By following these temperatures and behaviours for some years, the created simulation models can be adjusted for further evaluations in the coming traffic tunnel projects. Also, when long-term experiences concerning the thermal behaviours are gained, the optimization of the whole insulation system together with the need of heating cables can

be further analyzed. Further, the monitoring and simulation systems together with deeper understanding of the thermal phenomena make it possible to integrate 2D and 3D thermal and aerodynamic simulations by using aerodynamic boundary conditions as airflow caused by wind, ventilation and vehicles or trains together with thermal parameters of weather and tunnel structures.

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