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Design of Tunnel Structures and linings for ice pressure

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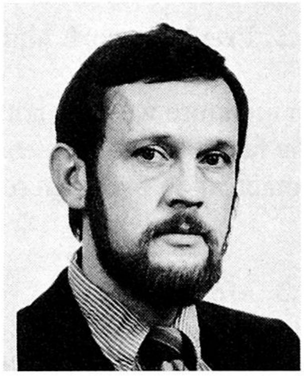

Summary

The normal procedure for design of tunnels in soil or rock is to drain out water that flow into the tunnel. In geotechnically sensitive areas were lowering of the ground water table will result in settlement of the soil, it is not allowed to drain out the water. An interesting question is then, if there is a risk for the formation of ice between the tunnel lining and the rock or soil.

A computer program has been developed for the non-linear calculation of temperature variation in tunnel linings on soil and rock. Special emphasis was laid on the proper modelling of the non-linear ice forming energy loss and gain during the freeze and thaw process. It is believed that this problem has been solved by the program and the results are in close agreement with measurements and other applied tests.

The calculation shows that the temperatures behind the linings could become below –2°C during cold winters. The frost depth and the amount of water that could freeze is normally though not enough to form pressures greater than the load carrying capacity of the actual tunnel linings.

1. Definition of the problem

This paper is concentrated on problems actual for studying the risk for forming of ice pressures around concrete linings of the type that projected for the Ring Road in Stockholm.

1.1 Questions

For many of the planned tunnels in Stockholm there are some very special design parameters. The tunnels have to be tight not to lower the ground water table. Lowering of the ground water could result in settlements in the soft soils adjacent to the tunnels, which in turn could cause great damage to many old buildings. The concrete tunnels are thus constructed water tight and in rock the rock is tightened using injection.

The above-mentioned design restrictions results in that full water load and load from the soils should be considered in the design. In countries with cold winter climate and for tunnels with good ventilation the temperature will for long time during the winter have temperatures below zero. A special question is then if there is a risk for the formation of ice pressure behind the linings.

1.2 Previous work and external references

In literature we have not found any information regarding this problem. This is probably due to the fact that this problem have not been met before, because few tunnels are constructed with this combination of design restrictions.

1.3 Measurements

In one older tunnel in Stockholm measurements have been made for measuring the temperature variation from the openings and on different stations in the tunnel. The temperature variation on different depths in the linings have also been measured for a couple of years. Of course such a short period will not show extreme and interesting results. Some verifying comparisons with the theoretical calculations have though been carried out.

2. Ice pressure

2.1 Interaction between temperature and pressure for water and ice

There is a relation between pressure and temperature that decides whether the water transforms into ice or not, see *Figure 1*. The figure shows that in a totally closed, non-expandable volume, very large pressures arises. Since the water expands approx. 9 % when transformed into ordinary ice, one can see that extra volume is needed to cope with the expansion. Most materials are porous and contains volumes in which the ice can expand.

There is also a relation between the size of the volumes in which freezing occur and the freezing temperature, see *Figure 2*. The figure shows the relation between equivalent radius of pores and the freezing temperature.

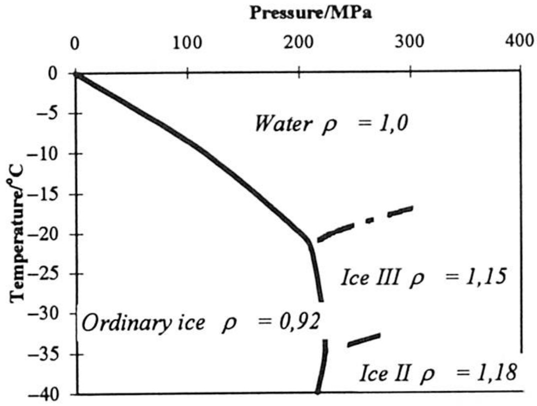

Figure 1 Relation between temperature and pressure and ice formation.

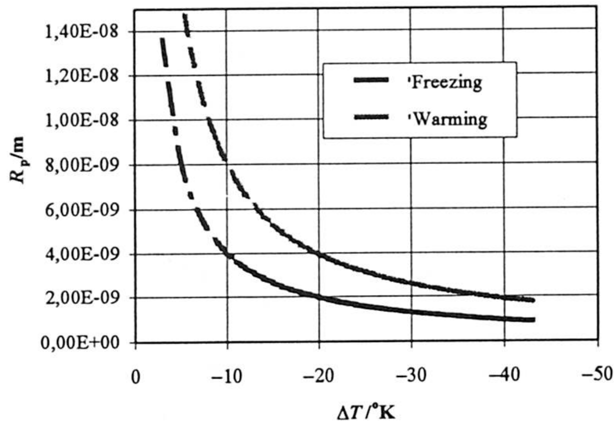

Figure 2 Relation between equivalent size of volume and the lowering of freezing temperature.

The problems discussed in this paper are closely related to the problem of frost in ground. For frost heaving in ground there has been set up relations between frost and ground heaving. The pressures actual in those cases are however much smaller than the ones discussed in this paper. Extrapolation of values for frost in ground shows that the risk for large pressures should be small even in the case of tunnels in soil. For the rock case no information could be found in the literature.

2.2 Reduction of pressures due to deformable structure

A pressure could not be built up if there is no structure to resist the volume change. As an example we assume we have a circular pipe formed tunnel structure acted on by a pressure from the outside. The resistance the pipe makes against this pressure could be evaluated by the formula

$$p = 0{,}1E\frac{w_\mathrm{h}t_\mathrm{j}t_\mathrm{k}}{R^2} \qquad \text{(a)}$$

where

- p pressure, MPa
- E Young's modulus of elasticity, MPa
- w_h water content in the surrounding material, %
- t_j thickness of the frozen soil or rock, m
- t_k concrete thickness, m
- R radius of the tunnel, m

Equation (a) is shown in *Figure 3*. The figure is based on a tunnel with 10 m radius and the pressure is plotted against 'effective ice thickness', t_eff. t_eff is defined by equation (b).

$$t_\mathrm{eff} = (w_\mathrm{h} - w_\mathrm{p})\cdot t_\mathrm{k} \qquad \text{(b)}$$

where w_p is the air content of the soil in %.

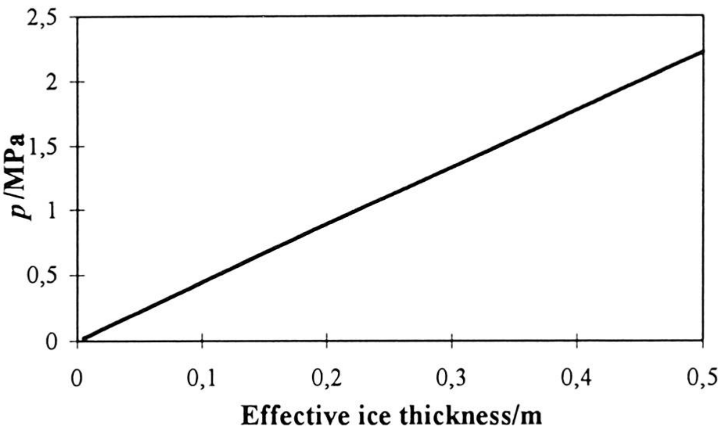

Figure 3 *Example of relation between 'effective ice thickness' and pressure against a tunnel structure. Effective ice thickness is equvivalent to the amount of water that could freeze.*

3. Analysis

3.1 General

A computer program has been developed for the linear and non-linear calculation of temperature variation in tunnel linings in soil and rock. Special emphasis was laid on the proper modelling of the non-linear behaviour of the process.

The computer program has the capability to take different parameters into account such as:

- Temperature variation in the tunnel
- Different material layers such as concrete, rock, soils with different water content, insulation, air voids and water filled pores
- Ice forming energy gain and loss during the freeze and thaw cycles.

3.2 Results without consideration of the ice forming energy

A problem not so complicated to analyse is the case when the temperature varies outside a infinite half-space. *Figure 4* and *Figure 5* show how the temperature varies at various depths inside a structure when the outside temperature varies sinusoidal with the amplitude T_{max}. In *Figure 4* the wavelength is 1 day and night and in *Figure 5* the wavelength is one week. 4 different lining structures are considered, a thin 50 mm concrete lining (i.e. shotcrete on rock), 400 mm concrete on rock and finally 1000 mm concrete without and with insulation. The calculations are based on the following material properties:

Concrete, thermal conductivity 1,8 W/(m·K) and specific heat capacity $2{,}5 \cdot 10^6$ J/(m^3·K) = 0,7 kWh/(m^3·K).

Insulation, thermal conductivity 0,05 W/(m·K) and specific heat capacity $0{,}1 \cdot 10^6$ J/(m^3·K).

Rock, thermal conductivity 4,0 W/(m·K) and specific heat capacity $2{,}0 \cdot 10^6$ J/(m^3·K).

Soil, thermal conductivity 2,1 W/(m·K) and specific heat capacity $2{,}5 \cdot 10^6$ J/(m^3·K).

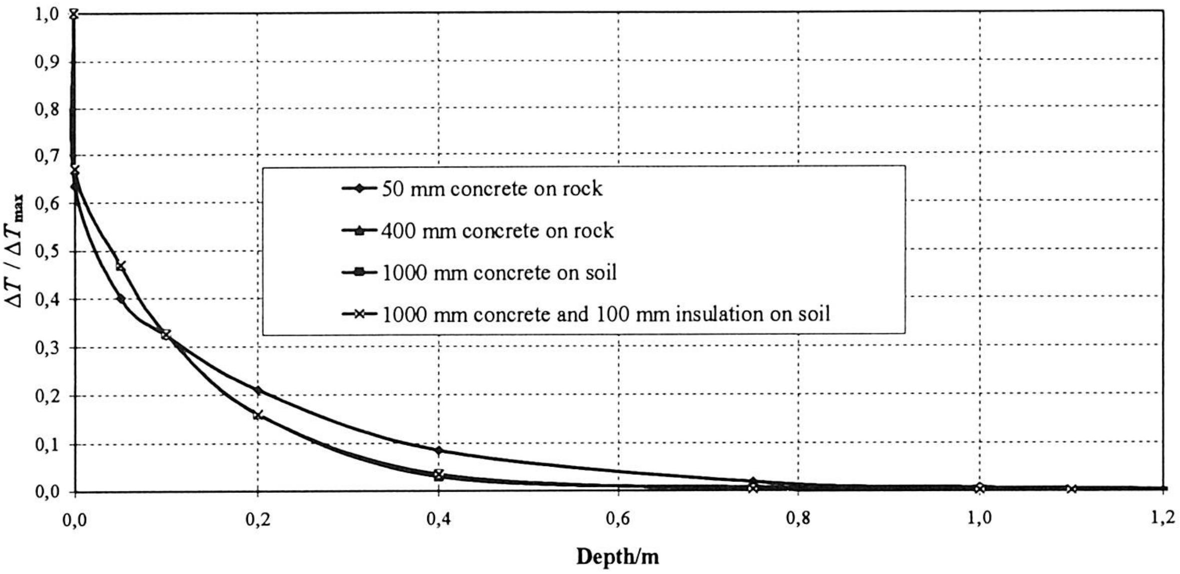

Figure 4 *Temperature variation ΔT at different depths in a lining when the temperature is varied with a period of one day and night with the amplitude ΔT_{max}.*

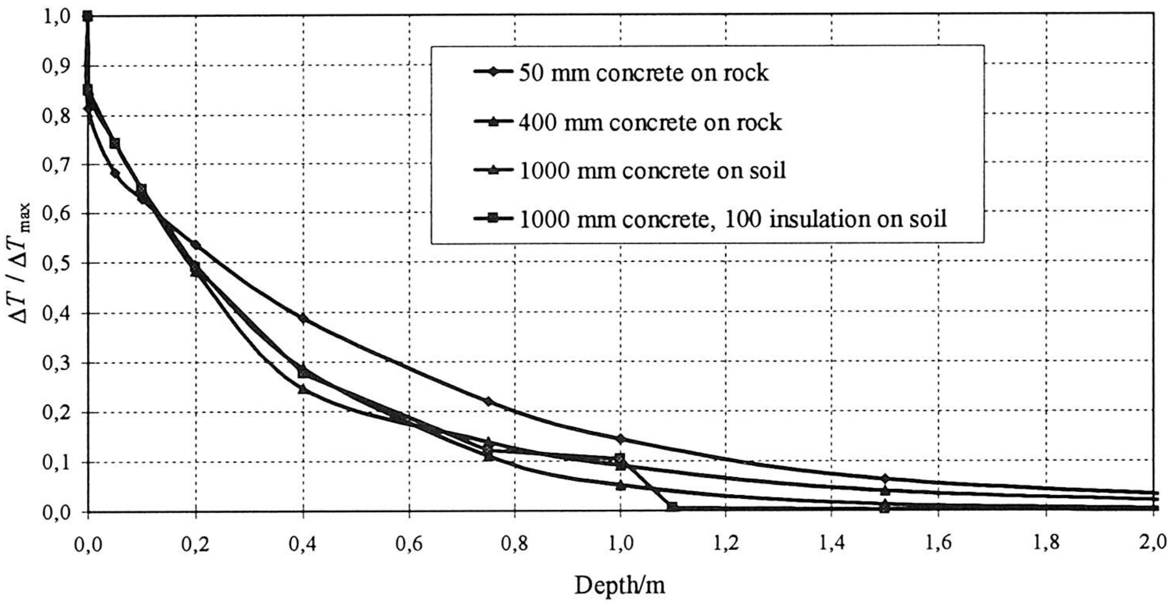

Figure 5 *Temperature variation ΔT at different depths in a lining when the temperature is varied with a period of one week with the amplitude ΔT_{max}.*

3.3 Results with consideration of the ice forming energy

Water might cause problems when cyclic freezing and thawing of the boundary between lining and rock occur. The reason to this is the possibility for the water to rearrange. It is therefore interesting to investigate by which frequency there is a temperature amplitude of 2K, 400 mm from the concrete surface in the case when we have a 400 mm concrete lining on rock. –2 °C is the temperature when we assume that water in concrete is transformed into ice.

In this study the heat transfer resistance in the air/concrete interface was given the value 0,033 $m^3 \cdot K/W$. The same values for material properties as before has been used.

Temperature cycles longer than one day has to be some kind of change of the weather. In *Krus* the best value, for the amplitude of this kind of temperature cycles in Stockholm was found to be around 10 K.

In order to investigate the most dangerous wavelengths, amplitudes between +4°C and –6°C were applied. For 6 day long cycles and 400 mm concrete on rock, results according to *Figure 6* were obtained. The water content in concrete was assumed to bee 1 % in concrete and 0,1 % in rock.

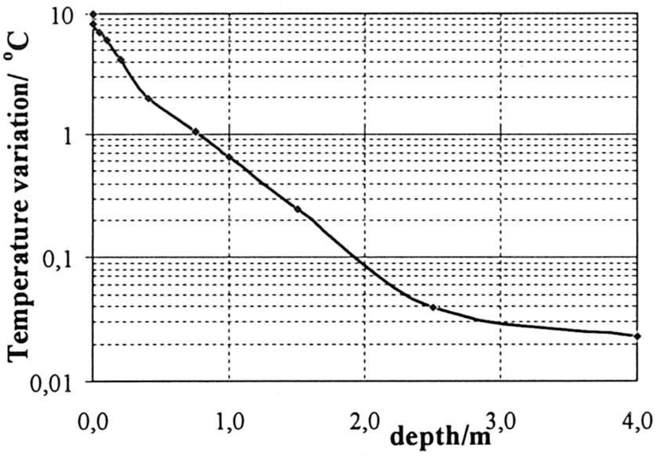

Figure 6 *Temperature penetration when the outer temperature varies in 6 day cycles (+4°C to –6°C) for a 400 mm concrete lining on rock.*

As can been seen in *Figure 6* temperature amplitudes with magnitude 2 K penetrated 400 mm into the structure. For other frequencies for the wavelengths, results according to *Figure 7* were obtained.
As can be seen from Figure 7 the penetration to an amplitude ΔT of 2 K is:

1 day and night	0,15 m
3 days	0,28 m
6 days	0,4 m
2 weeks	0,8 m

Since the calculations are close to 0 °C the energy loss and gain when the ice melts and freezes moderate the amplitudes at each cycle.

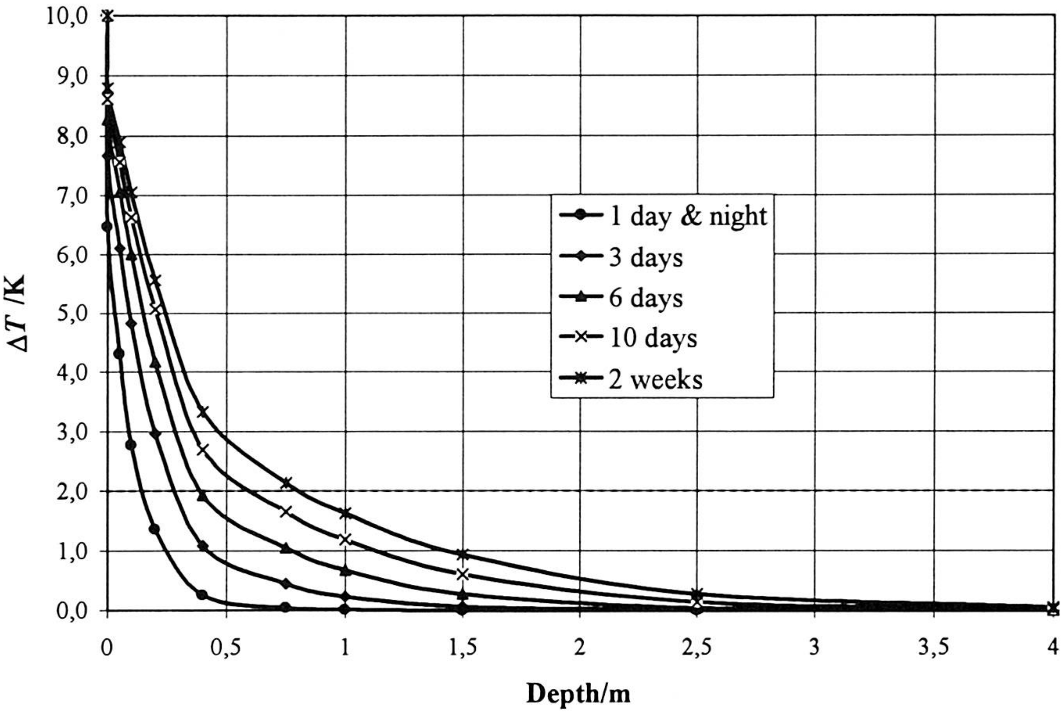

Figure 7 *Temperature penetration at different depths when the outer temperature varies in 6 day cycles for a 400 mm concrete lining on rock.*

In the special Swedish design code for tunnels there is a special design curve, see *Figure 8*, for the lowest design temperature, that should be considered regarding the risk for formation of ice in tunnels.

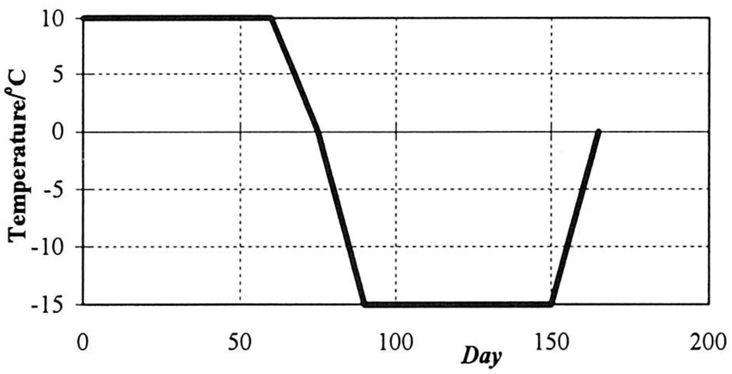

Figure 8 *Variation of dimensioning winter temperature according to the Tunnel Code of the Swedish Road Administration.*

Applying the temperature curve according to *Figure 8* calculations of the penetration have been made for two cases, namely 400 mm concrete on rock, *Figure 9*, and 1000 mm concrete on soil, *Figure 10*.

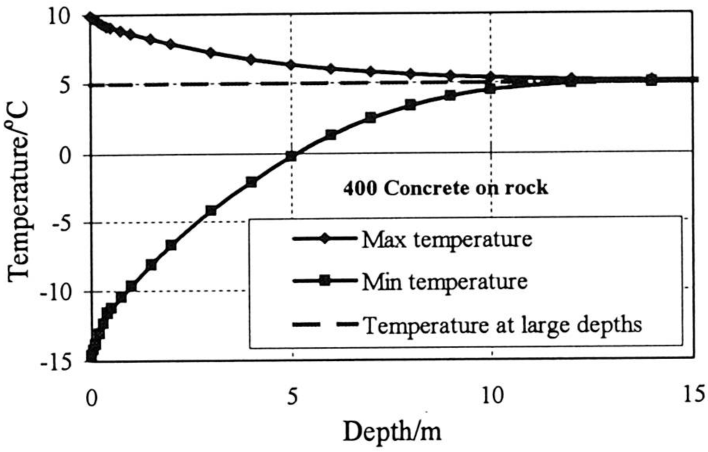

Figure 9 *Temperature penetration for the winter according to Figure 8 into a lining with a thickness of 400 mm on rock.*

As can be seen in *Figure 9* the variation in amplitude reached 12 - 13 m into the rock. 0 °C penetrated 5 m and –2 °C penetrated 4 m.

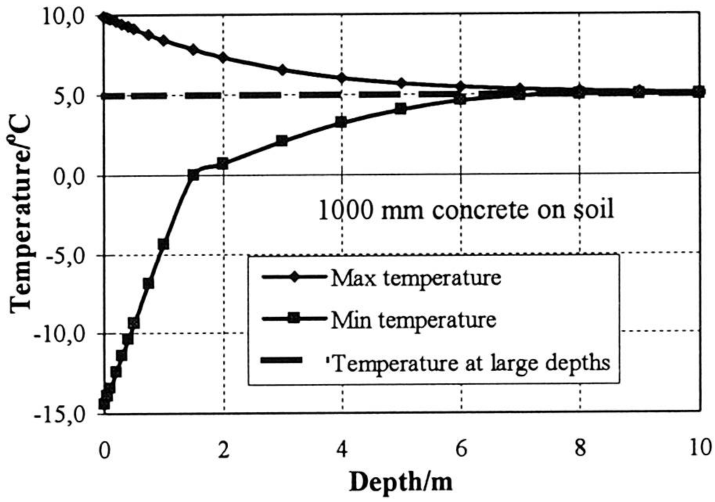

Figure 10 *Temperature penetration for the winter according to Figure 8 into a lining with a thickness of 1000 mm on soil.*

As can be seen in *Figure 10* the variation in amplitude reached 8 - 9 m into the rock. 0 °C penetrated 1,8 m and –2 °C penetrated 1,5 m.

An other question of importance is the influence of the moisture content in the concrete. Results of calculations showing this variation are shown in *Figure 11*. In *Figure 11* the amplitude at the air/concrete interface is 5,7 K in winter. As can be seen in *Figure 11* the variation in moisture content makes very little difference in the penetration depths.

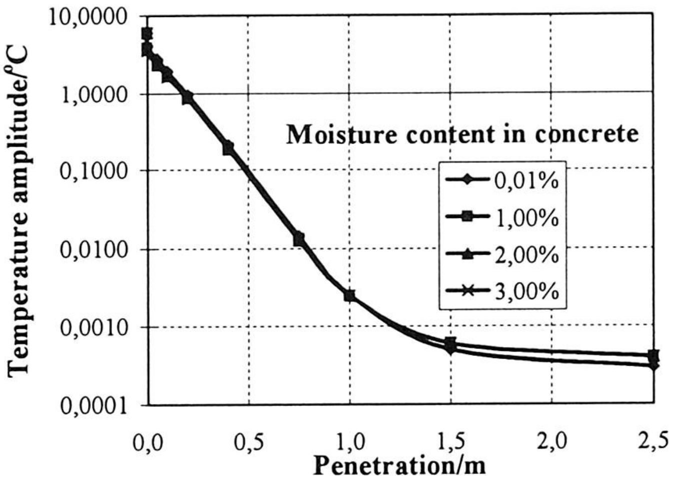

Figure 11 *Temperature penetration for an amplitude of 6 K from +2 °C to –4 °C for different moisture contents in the concrete.*

4. Conclusion and proposal for interpretation of results

A computer model has been set up for analysing the risk for hazardous formation of ice behind concrete linings in rock or soil. The non-linear computer model has the ability to calculate the penetration of frost into the materials around the tunnel for different material combinations an with varying temperatures. The calculations alone does however not solve the problem. There must also be a model for the pressures formed by the ice. The crucial parameter is then the amount of free water that is present in the rock or soil and that could freeze.

The combination of analysing the theoretical results and the engineering judgement of the possible amount of water present leads to the conclusion that the risk for ice pressures higher than the water pressure is very small. If a larger cavity between the lining and rock could be formed there could exist a risk. With god workmanship this risk seems to be small and thus the ice pressure could be neglected.

This paper is based on a small investigation, initially as a by-product from investigations regarding the risk for degradation of concrete bridges due to freeze-thaw cycling. Problems of this kind are very complicated if one tries to find what really happens inside the materials. The aim of the current investigation has consequently been to find an engineers on-the-safe-side solution to the stated problem.

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