Frost monitoring of the Finnish road network

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Abstract. At present, maintenance of road networks is one of the main functions of the Nordic road administrations and also the budget area where the largest expenditures exist. Managing and predicting maintenance needs makes it possible to focus the scarce resources available to where they are most needed. The better and more accurately we can assess road deterioration, the easier it becomes to plan long-term and cost-effective maintenance processes. The risks posed by e.g. climate change require more comprehensive tools with interactive data managing than what is currently available. In the spring, the road structures are most vulnerable when the frost thaws and the water remaining in the structures begins to dissolve. Unabsorbed water decreases road load capacity. Frost data monitoring is important information for predicting the behavior of the road network. It is important to know when the melted water has evaporated and drained off to be sure that it is safe for heavy vehicles to use the road again. The data also helps to work systematically. For example, it can be used to plan schedules for routing fitness measurements and paving and road repairs. The data is also helpful in frost damage surveys. This paper examines the frost penetration based on real-time in-situ monitoring. The study includes the construction of the in-situ monitoring network and calculational analysis of the frost penetration and thaw. The research presents results for frost penetration cycles in different parts of Finland and also presents the change of the cyclic patterns.

1. Introduction

A road network is a major asset for countries providing a base for accessibility. In total, the Finnish road network is approximately 454 000 km long. This includes around 350 000 km of private and forest roads and 26 000 km of municipal streets. The Finnish Transport Agency (FTA) is responsible for approximately 78 000 km. The majority of this, 64 900 km, consists of regional and connecting roads. However, these represent just over one-third of all traffic. Approximately 65% of the highways, or some 52 000 km, are paved [1,2,3]

A major role of national road network authorities is to maintain the network properly: to preserve the asset value and to provide users with safe transportation. To accomplish these targets a vast amount of road data is collected and used for planning and managing the road network.

At present, maintenance of road networks is one of the main functions of the Nordic road administrations and also the budget area where the largest expenditures exist. Managing and predicting maintenance needs makes it possible to focus the scarce resources available to where they are most needed. The decisions of maintenance can be based on both the history of the road structures and more accurate deterioration prediction. It can also be utilized in the construction and maintenance of areas that are significantly affected by the loading of heavy vehicles.
The better and more accurately we can assess road deterioration, the easier it becomes to plan long-term and cost-effective maintenance processes. The risks posed by e.g. climate change require more comprehensive tools with interactive data managing than what is currently available. Frost data monitoring is important information for predicting the behavior of the road network.

In the spring, the road structures are most vulnerable when the frost thaws and the water remaining in the structures begins to dissolve. Unabsorbed water decreases road load capacity. This research examines the frost penetration based on real-time in-situ monitoring and presents results for frost penetration cycles in different parts of Finland.

2. Freeze-thaw effects on pavement

Variation of the unsaturated state and the hydraulic hysteresis in granular materials of the pavement have a significant influence on the mechanical behavior of the materials. Water has a lubricating effect at contacts between particles, which is associated with a decrease in resilient modulus. Moreover, the mechanical properties of well-graded materials with higher fines content are more sensitive to water because water is more readily held in the pores. [4,5]

Frozen ground is defined as soil reaching a temperature below the freezing point of clear water (0 °C). The ice in coarse soil acts as a bonding agent that holds adjacent soil particles together. The bonding strengthens and decreases the water permeability of the frozen soil. In bituminous layers, decreasing temperature affects the binder, increasing the stiffness. [6]

The frozen ground can be divided into different zones top-down: frozen soil, ice lenses, frozen fringe, and unfrozen soil. The physical properties of frozen ground depend on the freezing and thawing process and the time-dependent temperature variation. [6]

It has been observed that frozen soils expand in volume more than only the water phase change can cause. With normal soil void ratios and water content, the overall expansion of 2 to 3 % of original soil mass should be expected. This major additional expansion called frost heave results from the migration of water from the unfrozen soil below to the frozen fringe and the formation of distinct ice lenses in the soil, which is known as ice segregation. [6]

On soil thawing, the ice melts. The melting and drainage conditions differ depending on the condition of the pavement. As the ice melts and turns to liquid, moisture content of the soil increases since water cannot drain out of the soil fast enough. Subsequently, the subgrade becomes substantially weaker and tends to lose bearing capacity. The increased moisture content leads to a potential risk of high pore-water pressure, which may greatly reduce the shear strength of the soil. [7]

To mitigate sudden displacements during the life of a structure or of a natural deposit, it is important to predict the deformation of soils induced by the wetting process, as unsaturated soils may either swell or shrink when they experience a wetting path. This is a function of the initial conditions in terms of void ratio and water content. [8]

Erlingsson and Sævarsdottir & Erlingsson studied pavement structures in controlled conditions. According to Erlingsson, raising the groundwater table increased both the resilient and the permanent strains in all unbound layers above the groundwater table in the pavement structure. Sævarsdottir & Erlingsson found that all the unbound layers showed increased permanent deformation as the water content increased, with the most dramatic increase in the subgrade where the largest increase in the water content was observed. The raised water level in the structure had a significant effect on the structure as it increased the water content in the unbound material layers, causing the resilient stiffness to reduce. The change in the vertical strain and the resilient modulus was found to be higher in the subbase than in the subgrade, despite a larger increase in the water content and a higher fine content in the subgrade material compared with the subbase. [9,10,11]

In addition, Ishikawa et al. studied that continuous cyclic freeze-thaw can cause degradation of the granular base which can decrease the fatigue life of asphalt pavement up to 80 % compared to the fatigue life estimated without considering the freeze-thaw and water content change of base layer. [12]
3. Presentation of frost data
Frost data monitoring is important information for predicting the behavior of the road network. It is valued in logistic control of transportation and setting lower road weather forecasts and weight limits. It is important to know when the melted water has evaporated and drained to be sure that it is safe for heavy vehicles to use the road again. The data also helps to work systematically. For example, it can be used to plan schedules for routing fitness measurements and paving and road repairs. By reviewing accurate real-time data, one can be sure when the frost has truly thawed and thereby plan the best possible timing for repairment process. The frost forecast founded on history data can work as a guideline for next year’s planning. In addition, the data is helpful in frost damage surveys. The history data is automatically saved and easy to interpret.

Frost depth calculation can be done to every individual point in Finland. It is based on altogether 700 road weather stations and regular weather stations. The frost depth calculation method is presented in chapter four. The frost depth calculations have been compared to measured temperature profiles in a few points, and the results between these two methods have been very similar. In Figure 1 are presented the measured field temperatures and below that the calculated frost-depth model at the same time scale.

![Image of frost data comparison](image)

**Figure 1.** Temperature based frost depth monitoring compared to calculation-based frost depth monitoring in the same point.

4. Frost data analysis for a specific point
FinMeas has developed an automatic frost depth calculation method and graphical interface for viewing data. The algorithm enables frost depth estimate calculation to any measured point in which the temperature history from weather stations is available. The calculation in each point is generated by using two nearest weather stations. The distance of the weather stations is considered, for example the data from the nearest of the two weather stations is emphasized in calculations. Freezing index is calculated from the data, and using the-freezing index the frost level can be defined by using equation 1,

\[ z_f = k \sqrt{F} \] (1)
in which $z_f$ is frost depth from the ground surface, $k$ is a ground type-specific factor and $F$ is the freezing index.

In addition, the model includes a melting analysis, which is calculated by using the delta T-model. During the melting period, frost starts to melt mainly from the surface. If a colder period occurs again during the thawing season, the model calculates the freezing upward from the bottom of the thawed layer. The model also estimates melting happening from the below and includes forecast for the frost. Forecast calculation is based on ten years of historical data, from where an hourly average of temperatures is calculated for each hour of the year. The data can be generated to any point in the Finnish road network.

The biggest challenges of the model are related to changes in microclimates within small areas. For example, the temperature and amount of sun on the surface can differ within small areas, which can lead to be differences between calculated and real frost depth. In addition, the model is based on the assumption that no snow exists at the location where the frost depth is calculated. In practice, these challenges mean that the calculated frost level might be in some situations deeper than the real frost level.

5. Frost depth analysis of Finnish road network

Data was gathered from 47 locations distributed evenly around Finland, shown in Figure 2.

Based on the FinMeas frost-depth data, on average the first frost is seen at the start of November at the northern parts of Finland, and the frost front travels to the south in one to two months. The melting advances in the opposite direction, starting from the south on average in April and reaching the northern parts in approximately two months in June. The average frost depth on a frosting period reaches 2.5 meters in the north and 0.5 to 1.0 meters in the south. The average time that some parts of the ground are frozen is 250 to 300 days in the north and 100 to 150 days in the south of Finland. For example, see the comparison between the frost data between Helsinki in southern Finland and Utsjoki, the most northern city in Finland shown in Figure 3 and Figure 4. Both figures show a typical northern frost history for Utsjoki with a continuous frost layer between the start and the end of the time series. In the year 2016 Helsinki had a similar shape for the frost history as Utsjoki, but for 2017 multiple freeze-thaw cycles can be seen in the time-series.

To study the melting effect, a condition where the frost is still present, but ground consists of liquid water on top of the frozen layer, the melting-effect days were calculated for specified points seen in Figure 5. On average the melting-effect duration is longer in the northern parts, 80 to 140 days compared to the 40 to 100 in the south. The temporal location of the melting effect is distributed more evenly through the whole frosting period while the melting effect is clearly focused on the end of the frosting period. Figure 6 presents the effect of cycles of melt-frost periods. Each melt-frost period contains temporal range which starts when the upper melting amount exceeds 0.10 m and ends either when the frost vanishes or the upper melting amount decreases to values less than 0.10 m. In northern parts of Finland, the cycles of melt-frost are low (typically 1 to 4) whereas in southern Finland the cycles can occur up to 10 times. The more frequent cycles can cause e.g. degradation of the granular base, or the increased moisture content above frozen layer can lead to a potential risk of high pore-water pressure.
Figure 2. Data locations for the frost-depth analysis.
Figure 3. Frost depth calculations for Helsinki (P47) and Utsjoki (P04) in 2016, locations are shown in Figure 2. The lower line describes the evolution for the bottom of the frost and the upper line describes the amount of melted ground between the surface and frost bottom.

Figure 4. Frost depth calculations for Helsinki (P47) and Utsjoki (P04) in 2017, locations are shown in Figure 2. The lower line describes the evolution for the bottom of the frost and the upper line describes the amount of melted ground between the surface and frost bottom.
Figure 5. Relationship between Frost days and Melt-Frost days, for data, gathered between 2011 and 2019. Point locations are presented in Figure 2.

Figure 6. Cycles of melt-frost periods, for data, gathered between 2011 and 2019. Point locations are presented in Figure 2.
6. Conclusions
Pavement structures undergoing freezing and thawing are subjected to a great variation of environmental conditions inducing various loadings and stresses. During freezing, uneven frost heave can cause deterioration of pavement service performance. During thawing, the pavement can weaken significantly due to the accumulation of meltwater in the structure or the subgrade. The increased moisture content leads to a potential risk of high pore-water pressure, which may greatly reduce the shear strength of the soil. The effects caused by melting combined with heavy traffic loading can cause significant damage to the pavement surface and to the granular layers leading to pavement deformation.

Calculation based frost depth model represents the frost situation in a very realistic way. The melting-period model and forecast give relevant information for the planning of different works related to frost situation. One important information is to get an estimate when the frost is melted completely. In addition, during the melting period it’s important to notice that frost typically blocks water above it. This means that partly melted ground might be very wet and has a limited load capacity. Based on the temporal behavior of the melting effect, southern locations have a higher risks to lead to a situation where the load capacity is exceeded, which can cause deformation in the road structures eventually leading to breakage. In future research, the effect of freeze-thaw cycles and rut depth measurement history should be combined to evaluate their correlation between the increase of rut depth and cyclic freeze-thaw. The results can be used to assess the effect of climate change where the cyclic freeze-thaw phenomena may increase in the northern parts of Finland.

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