# Modification of the FMI Road weather model to forecast spring thaw weakening – literature overview

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The purpose of this literature overview is to gather necessary information to modify the road weather model to forecast spring thaw weakening. The purpose is not to give all-encompassing picture of the scientific field.

## 1. Introduction

The spring thaw weakening in gravel roads can be caused either by surface thaw weakening or structural thaw weakening (Saarenketo & Aho 2005, metsähoidonsuositukset.fi). Surface thaw weakening occurs during springtime when the road surface melts, but the deeper road layers remain frozen. This prevents the melting water infiltration into ground and causes the road to become muddy. The surface water content affects to the severity of the surface thaw weakening. If the road was very wet when the freezing occurred, the weakening is more severe. The structural thaw weakening is caused by ice lenses melting in the road structure. Ice lenses are formed when the road gradually freezes, and capillary effect causes water to rise toward the frozen layer. This water forms ice lenses when freezing. The size of the ice lenses can vary from millimeters to tens of centimeters. Ice lens formation requires the freezing process to be relatively slow. They are not formed if the freezing is fast. At spring these ice lenses start to melt and the hydrostatic pressure caused by heavy vehicles forces the water to flow upwards and sideways. This reduces the bearing capacity of the road and can cause the road material to flow up to the road centre or beside the road (Saarenketo & Aho 2005, metsähoidonsuositukset 2021).

Spring thaw weakening can also cause damage to paved roads (Saarenketo & Aho 2005). If the material under the pavement is frost susceptible, the thawing can cause a saturated layer between the pavement and the frozen road structure. Heavy vehicles cause hydrostatic pressure which can lead to pavement deformations, cracking or potholing. Later in the spring, thawing in the deeper road layers can also cause pavement deformation (Saarenketo & Aho 2005).

Weather conditions have considerable impacts to the severity of spring thaw weakening (Launonen & Turunen 1995). Generally, rainy falls and mild winters mean higher water content and slower freezing, which causes the spring thaw weakening to be more severe. Cold weather at the start of the winter means faster freezing and lack of ice lenses, which lead to meager spring thaw weakening.

To get the FMI road weather model to predict the spring thaw weakening on gravel roads, several model modifications should be made. First, the physical properties of the road structure should be modified to correspond the gravel roads. Second, the water transportation in the soil needs to be added to the model. This includes water drainage to ditches. Third, the formation and melting of the ice lenses needs to be modelled. Fourth, the effect of a snow layer on the road needs to be considered. Lastly, an algorithm needs to be made to determine the severity of the spring thaw weakening depending on the moisture and temperature profiles in the road.

## 2. Water transportation modelling

There are several models that simulate soil moisture dynamics (Zha et al 2019). One such model is open-source APES (Atmosphere-Plant Exchange Simulator) that is developed in National resources institute Finland (Launiainen et al 2015). Parts of the code related to water flow will be taken from APES and implemented to the road weather model.

Richards equation is widely used to model variably saturated soil water flow (Dam & Feddes 2000). The equation includes infiltration, evaporation, capillary rise, lateral flow, drain flow and deep percolation (Nickman 2016). In vertical dimension it can be written as:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} - S(h) \tag{1}$$

where C is water capacity derivative (dθ/dh), θ is water content, h is water pressure head, t is time, K is the unsaturated hydraulic conductivity, z is depth (positive upward), and S is root water extraction (Dam & Feddes 2000). Solving Richards equation is not straightforward because it is nonlinear and has a parabolic form. Several studies exist about optimal solution for the equation (Dam & Feddes 2000; Zha et al 2019; List and Radu 2016). APES model uses implicit, finite difference scheme presented by Dam & Feddes (2000):

$$\begin{aligned} C_i^{j+1,p-1}\left(h_i^{j+1,p} - h_i^{j+1,p-1}\right) + \theta_i^{j+1,p-1} - \theta_i^{j} \\ = \frac{\Delta t^j}{\Delta z_i}\left[K_{i-(1/2)}^{j}\left(\frac{h_{i-1}^{j+1,p} - h_i^{j+1,p}}{\Delta z_u}\right) + K_{i-(1/2)}^{j} \right. \\ \left. - K_{i+(1/2)}^{j}\left(\frac{h_i^{j+1,p} - h_{i+1}^{j+1,p}}{\Delta z_l}\right) - K_{i+(1/2)}^{j}\right] - \Delta t^j S_i^j \end{aligned} \tag{2}$$

The ground is divided to separate layers and calculation nodes (i) are set to the centre of each layer. Node numbering increases downwards. Subscript j refers to the time step and p to the iteration step. $\Delta t^j$ means the time difference between time steps j+1 and j, $\Delta z_u$ the height difference between nodes i-1 and I, $\Delta z_l$ the height difference between nodes I and i+1 and $\Delta z_i$ is the layer thickness. $K_{i-(1/2)}^{j}$ means the arithmetic mean of K between the nodes i and i-1 and $K_{i+(1/2)}^{j}$ between the nodes i and i+1. K and S are calculated for the time step j. In the implementation to the road weather model, root water uptake (S) is replaced by drainage to ditches. Equation ( 2 ) is applied to each node, which results in a tri-diagonal system of equations, which can be efficiently solved. Full explanation including equations for the top and bottom nodes are given by Dam & Feddes (2000).

Water retention curve is used to link the soil water content as a function of pressure head (Genuchten 1980, Launiainen et al 2015):

$$\theta(h) = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{(1 + |\alpha + h_s|^n)^m} \tag{3}$$

where $\theta_{res}$ is the residual and $\theta_{sat}$ the saturated water content. The residual water content means the content of water in soil without water flow. α, n and m=1-1/n are empirical parameters that depend on soil type.

Drainage to ditches can be modeled by Hooghoudt's draining equation (Hooghoudt 1940) as done by Nickman et al (2016). Moriasi et al 2014 give equation in the following form:

$$q = \frac{8K_e d_e m + 4K_e m^2}{L^2} \tag{4}$$

where q is the water flow to ditches (mm/h), m is the water table height above the drainage level in the middle of the ditches (mm), $K_e$ is the effective lateral saturated hydraulic conductivity (mm/h), L is the distance between drains (mm) and $d_e$ is equivalent depth, which is a function of L, ditch radius and difference between the depth of the impermeable base and the drainage level. Drainage level means the depth of the water layer in the ditch measured from road surface. Above the drain level, the equation takes only into account the horizontal flow to the ditch, whereas below the drain level the equation takes into account both horizontal and radial flows. Hooghoudt's equation is usually used to model drainage in fields and it remains to be seen how well it performs for gravel roads.

### 3. Soil freezing

Freezing affects considerably the soil heat capacity and conductivity and reduces the water flow (Hansson et al. 2004). These effects are taken into account in the APES model, whose calculations are based on paper by Hansson et al (2004). Hansson et al (2004) present basic theory for water and heat transport and discuss the effects that freezing causes to the soil heat capacity and conductivity. When freezing point is reached, the soil heat capacity can increase several orders of magnitude in fully saturated soils depending on the soil class. The heat capacity reduces gradually when moving to lower temperatures. The water in soil does not necessarily freeze at precisely 0 °C because the interactions between soil particles and solutes affect to the freezing point (Beskow 1935). Ice conducts heat better than water, and thus the amount of ice in the soil has considerable effect on the soil heat conductivity. Hansson et al (2004) present an equation to take this effect into account.

When soil freezes slowly, the water flows to the freezing front where the freezing occurs. This process is similar to soil drying (Beskow 1935, Hansson 2004). The model presented by Hansson et al (2004) was able to simulate this effect well when compared to the laboratory simulations. However, the research by Hansson et al (2004) does not consider the formation of the ice lenses, which are considered an important factor in spring thaw weakening. Ice lenses are formed when freezing causes the formation of discrete layers of ice in the soil (Peppin et al 2013). Water migrates from the unfrozen regions of the soil and deposits as bands of pure ice (Figure 1). Ice lenses force soil layers apart as they grow, causing frost heaving. There are various mathematical models to explain frost heaving, which can be categorized to capillary models and frozen fringe models (Peppin et al 2013).

The capillary models rely on the Clapeyron equation that describes thermodynamic equilibrium in a system:

$$P_i - P_w = \frac{\rho_w L_f}{T_m}(T_m - T) \tag{5}$$

where $P_i$ is ice pressure, $P_w$ is water pressure, $\rho_w$ is the density of water, $L_f$ is the latent heat of fusion at the bulk freezing temperature $T_m$ and T is system temperature. When temperature is reduced and the ice lens pressure is constant, the ground water will be at relatively high pressure and the water flows upwards towards to the ice lens (Peppin et al 2013). Capillary theory assumes that the ice cannot invade the soil pores immediately as the temperature drops below freezing. The ice will penetrate the pores only when the temperature is low enough. When the ice fills the pores, it forms a frozen fringe and stops the water being sucked to the ice lens, preventing its growth. (Peppin et al 2013).

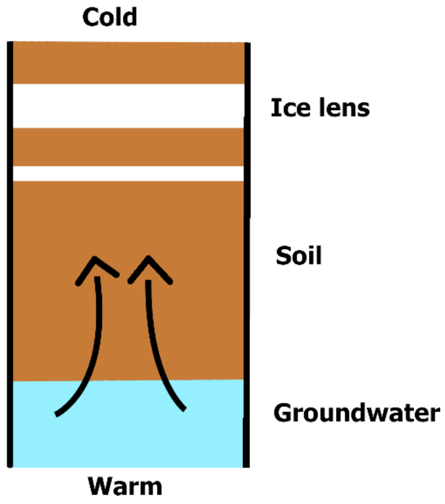

*Figure 1. Schematic diagram of ice lens formation*

The initial capillary models had several problems, although many have been resolved in the later research. These problems led to the development of frozen-fringe models, which explain the ice lens growth after a frozen fringe has formed. According to the theory, the frozen fringe contains premelted films, which allow the slow transport of water. Thermomolecular pressure gradients were shown to be the driving force behind this transport (Peppin et al 2013).

Ice lens formation is rather complicated topic, and although considerable progress has been done in recent years, there are still unanswered question (Peppin et al 2013). In order to model spring thaw weakening, it might be better to take statistical or machine learning based approach rather than model ice lens growth numerically.

## 4. Snow Layer

Although the FMI road weather model calculates the amount of snow on the road, the snow layer is not taken into account in the energy balance calculation except by increasing the road albedo. However, the snow layer can have a considerable effect on the road temperature as it isolates the surface from air. On private and public roads with less traffic, there can be a snow layer on the road for long periods in winter, so the effect of snow should be considered in the model. In previous research, Bouilloud and Martin (2006) present a model for road snowpack modeling that combines CROCUS snowpack model (Brun et al. 1989) and ISBA heat balance model (Noilhan and Mahfouf, 1996). The coupled model calculates heat balance of snow-covered surface as

$$c_T \frac{\partial T_s}{\partial t} = F_{cond} + F_{adv} + F_{sol} + G \tag{6}$$

where $c_T$ is the heat capacity of road surface layer, $T_s$ is the road surface temperature, $F_{cond}$ is the heat conduction flux between snow and road, $F_{adv}$ is the advection flux caused by water runoff from snow cover, $F_{sol}$ is the solar flux at the bottom of the snow cover, and G is the soil heat flux. The heat balance at the top of the snow layer is calculated similarly as in the RWM for snow free surface except that the parameters describe the snow layer. The CROCUS part of the coupled model calculates the heat conduction and water movement trough the snowpack. The snow thermal conductivity depends on many factors, like air and snow temperature, snow density and grain structure (Jafarov et al. 2014).

The coupled snow-road model takes into account the snowpack evolution, freezing, melting and grain type. It also parametrizes the water saturated snow layer under the snow cover which cause dangerous conditions when freezing. The thermal resistance calculation of the snow-road interface is rather detailed and it depends on whether the road and/or snow are frozen or not. However, the model does not consider the effects of traffic or deicing.

In order to include calculation of $F_{cond}$, $F_{adv}$ and $F_{sol}$, to FMI RWM, open-source SNOWPACK model could be utilized (Bartelt and Lehning, 2002). SNOWPACK is based on CROCUS model and is meant for avalanche prediction. It contains very detailed snowpack modeling that is not necessary for modeling road conditions, but parts of the model can be included in the RWM. However, like model presented by Bouilloud and Marting (2006) SNOWPACK does not take into account snow packing by traffic. This should be considered in the RWM, as packed snow has quite different physical properties than for example powder snow (Kinosita et al 1970). Traffic compacts the snow so that ice bonds are formed with snow grains, although the snow grain dimension remains the same (Kinosita et al 1970)

## 5. Gravel road structure

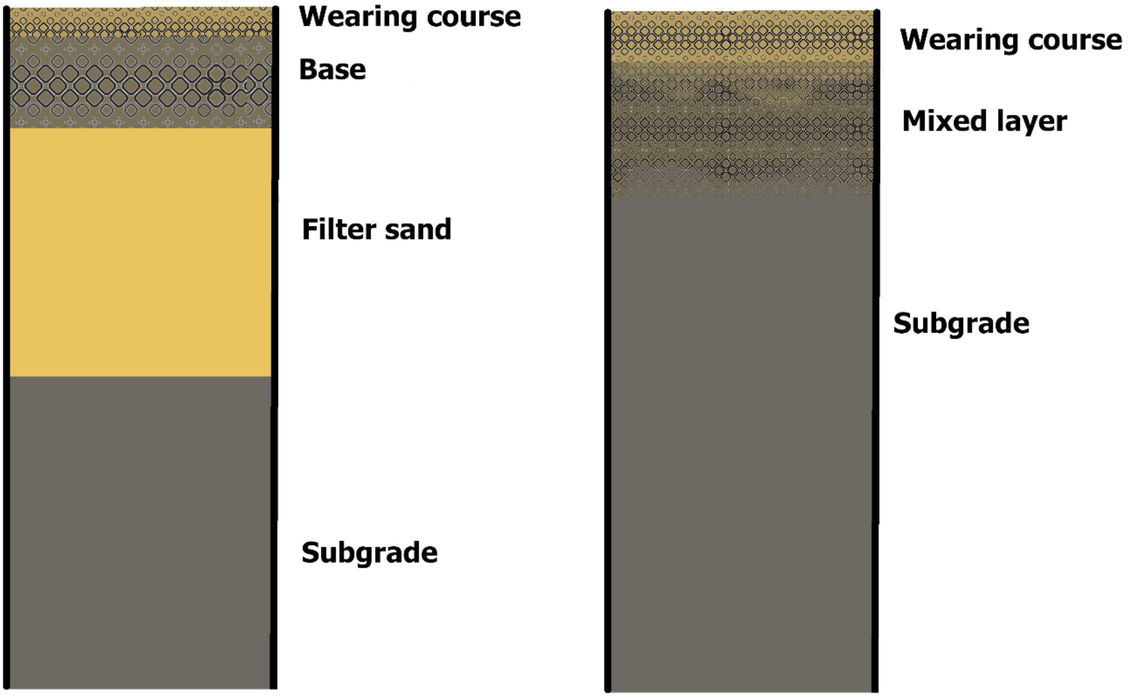

*Figure 2. Example structures of well build gravel road (left) and road with only wearing course (right).*

The physical properties of the road weather model should be modified to describe gravel road structure. Well build gravel roads are structured of several layers (Liikennevirasto 2014). At the top there is a wearing course which consist of crushed gravel (Figure 2). Crushed rocks and moraine can also be used. The maximum grain size is usually 16 mm. The recommended depths of the wearing course vary from 5 cm to 10 cm depending on the traffic amount on the road (Liikennevirasto 2018). The material should contain enough finer grains to make the structure solid. Below the wearing course there is a base, whose recommended depth varies from 10 cm to 56 cm depending on the subgrade soil. The base material is crushed rock or gravel (Tiehallinto 2004). Liikennevirasto (2018) does not mention the recommended grain sizes but Hämäläinen (2010) suggests 0-45 mm or 0-56 mm grain sizes for the base. Below the base course is either geotextile (filter cloth) or a layer of filter sand. The purpose of this filter layer is to decrease the amount of capillary water, prevent frost heaving and avoid the mixing of the subgrade and base materials (Destia 2021). The recommended depth of the sand layer varies from 230 cm to 540 cm depending on the road usage and subgrade soil.

Below the filter layer is the subgrade. The main soil types according to geotechnical soil classification are: peat, mud, clay, silt, sand, gravel, rocks, boulders, silt till, sand till and gravelly till (Liikennevirasto 2018). Soil type at certain location can be found for example by using map tool provided by Geological Survey of Finland (http://gtkdata.gtk.fi/maankamara/). The side ditches are important for drainage and they should be cleaned at least every 8 years (Saarenketo & Aho 2005). The depth of the side ditches should be at least 0.5 m from the road surface (Hämäläinen 2010). The recommended width of a gravel road is around 6 m (Liikennevirasto 2014).

However, most of the gravel roads are not well build and do not have frost heave preventing layers (Liikennevirasto 2014). Many roads have only a wearing course, and below that a mixed layer of subgrade soil and road material (Figure 2).

## 6. Physical properties of road materials

Many of the gravel road material physical properties can be easily found in literature (Table 1). However, most of the parameters have large variability ranges. Also, the soil is often a mix of different soil types. More accurate parameters can be estimated if the soil type is known in more detail. Empirical parameters of the water retention curve for gravel are not that easily available. However, there are some studies about the subject. One approach is to adjust the water retention curve for soil based on the gravel content (Khaleel & Relyea, 1997; Dann et al 2009). If the gravel contains nonporous rock fragments, it can be assumed that the moisture content is held entirely by the fine soil (Khaleel & Relyea, 1997). Then water content can be calculated as:

$$\theta^b = \theta_f(1 - V_r) \qquad (7)$$

where $\theta_f$ is volumetric moisture content of the fine fraction and $V_r$ if volume fraction of gravels. However, according to Wang et al (2013), the water held by gravel cannot be neglected as gravel has significant porosity and it changes the soil pore-size distribution. In their study, they conducted laboratory experiments for several soil gravel mixtures. For each type, they fitted water retention curves to measurement data and determined the empirical parameters. The best approach might be to test different parameters in the model and see which works the best. In an earlier study where CoupModel was used to model the water flow in the road, it was noted that the model was rather sensitive to retention parameters (Nickman et al 2006). Although their model used Brooks & Corey (1964) approach to model the water retention curve rather than Genuchten approach, attention should be paid to finding the right retention parameters for each forecast site.

*Table 1. Physical properties of different gravel road materials*

| | porosity (%), (Freeze & Cherry 1979) | bulk density (dry) ($\text{kg/m}^3$), (structx.com) | heat capacity, (MJ/(m3°C)) (Pahud, 2002) | thermal conductivity (dry) (W/m°C) (Pahud, 2002) | hydraulic conductivity (m/s) (Freeze & Cherry 1979) |
|---|---|---|---|---|---|
| gravel | 25-40 | 1442-2483 (gravel with silty sand) | 1.4-1.6 | 0.4-0.5 | $10^{-3}$-1 |
| sand | 25-50 | 1378-2371 | 1.3-1.6 | 0.3-0.8 | $10^{-6}$-$10^{-2}$ |
| silt | 35-50 | 1297-2179 | 1.5-1.6 | 0.4-1.0 | $10^{-9}$-$10^{-5}$ |
| clay | 40-70 | 1506-2130 | 1.5-1.6 | 0.4-1.0 | $10^{-12}$-$10^{-9}$ |

## 7. Conclusions

Based on the literature overview, modifying the FMI RWM for gravel roads is an arduous task. The first task will be to adjust the properties of the model layers to describe gravel roads and to add water transportation modeling. This will require testing with different parameters and checking which give the best results when compared to observations. After that, the processes of soil freezing and ice lens formation should be added. Modeling ice lens formation cannot be done in detail, but some parametrization scheme could be developed based on observation data. At this point, an algorithm describing spring thaw weakening severity will be developed. Finally, if water transportation and freezing processes can be successfully added to the model, algorithms taking into account the effect of the snow layer can be included.

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