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Equifinality and sensitivity in freezing and thawing simulations of laboratory and in situ data

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Abstract

Numerical models of soil freezing and thawing are being increasingly used in, e.g., agriculture, forestry, ecology and civil engineering. This study was conducted to 1) elucidate the sensitivity in simulation output to the variability of model parameters for the hydrodynamic model Hydrus-1D and 2) investigate how two operational considerations in the model setup, groundwater level and subgrade material (soil texture), affect indicators of road accessibility in northern Sweden. The analysis was carried out by applying the generalized likelihood uncertainty estimation (GLUE) procedure when simulating laboratory measurements of freezing cylinders and by a more conventional sensitivity analysis, varying one parameter at a time, using road surface temperatures measured during nearly 1 year as upper boundary condition. For the simulation of the laboratory experiment, it was found that, although the thermal conductivity scaling factor, λ_f, and the convective heat transfer coefficient, h_c, most strongly affected the output, no parameter was redundant for the given problem. The frost depth was most sensitive to changes in λ_f and h_c, while the water content in the unfrozen zone was most sensitive to changes in the hydraulic conductivity impedence parameter Ω. For the 1-year road simulation, the frost depth was larger for sand than for the loam and silt subgrades; the thawing period was shortest for sand and longest for the silt subgrade; and the silt subgrade allowed for the largest frost-induced upward water flow. Thus, among the subgrades studied, roads built on silt show the potential of being most frost-susceptible as a consequence of having the largest elevated water content in combination with the longest time of thawing. The study performed indicates that the model can provide information of interest from an operational perspective, allowing for local predictions important in the road construction and maintenance process.

Keywords: Soil freezing; Highways; Sensitivity analysis; Numerical models

1. Introduction

Numerical models of soil freezing and thawing are used in a number of applications in agricultural and

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forestry studies, as well as in engineering designs and constructions of, e.g., roads and airfields in cold regions. Most models have a physical base and describe the coupled transport of water and heat using various extended formulations of Darcy's and Fourier's equations. Over the last 30 years, two classes of soil freezing/thawing models have evolved, differing in the treatment of ice pressure. One group include the Harlan type hydrodynamic models (e.g., Harlan, 1973; Guymon and Luthin, 1974; Flerchinger and Saxton, 1989; Jansson and Karlberg, 2001). The models of the other group focus mainly on frost heave processes and are typically based on the work of Miller (1980) and O'Neill and Miller (2001). The central difference between the two groups of models is the treatment of the liquid water and ice pressures, where ice pressure is assumed constant in the hydrodynamic models and variable in the frost heave models. Frost heave is generated by changes in ice pressure and, thus, hydrodynamic models cannot in a physically correct way take these effects into account even though they can still produce empirical predictions of frost heave. On the other hand, the frost heave models mentioned above were derived for saturated conditions only, which severely limits their use, and evidence against the constant ice pressure hypothesis are rarely observed in practice unless significant heaving occurred (Spaans and Baker, 1996).

Common for all these models is that they require parameterisations, introducing limitations to operative utilisation and demanding parameter-values that are not easily obtained by laboratory or field experiments. Even the parameters that can be determined from straightforward experiments suffer from measurement uncertainties and often show considerable variability even over short distances. The latter fact has led to the development of large databases such as HYPRES (Wösten et al., 1999) and UNSODA (Nemes et al., 1999) as well as computer programs for prediction of hydraulic properties such as ROSETTA (Schaap et al., 2001), from which statistics of hydraulic properties can be obtained. Additional uncertainty is often introduced by poor control of boundary conditions. Hence, in many operational applications of numerical heat and water transport models, quite crude assumptions have to be made concerning hydraulic and thermal properties as well as boundary conditions needed to perform the simulations. It is thus important to investigate and, if possible, quantify the sensitivity in output due to uncertainty in model parameters and boundary conditions.

Flerchinger (1991) performed a sensitivity study using a model similar to Hydrus-1D; the one used in this study. He found, by varying one parameter at a time, that simulated frost depth was very sensitive to air temperature and sensitive to the bottom boundary condition when the simulated frost depth was close to the depth of the simulated profile. In contrast, he found that soil hydraulic properties had little effect on frost depth but had a large impact on freezing-induced water movement. Lytton et al. (1993) tested the sensitivity of predicted frost depth and frost heave of another similar model, the CRREL frost model. They found, in contrast to Flerchinger (1991), that the saturated hydraulic conductivity had a significant influence on frost depth. The contradicting results presented by these authors suggest a need for additional studies and, moreover, demonstrate that similar numerical codes often exhibit quite individual behaviour.

Familiarity with the influence of parameters and boundary conditions is crucial for a correct application of coupled water and heat flow models that include phase change between liquid water and ice since these models in general demonstrate a complex behaviour due to the many inter-dependencies between state variables. The present study focuses on the above aspects of the one-dimensional, combined finite difference and finite element model Hydrus-1D (Šimůnek et al., 1998; Scanlon et al., 2003), extended to include phase change (Hansson et al., 2004). The model is a hydrodynamic type model and does not explicitly account for frost heave. Considering that we were mostly interested in unsaturated materials, this type of model was considered the best choice even if frost heave may occur in roads.

It should be noticed in this context that snow cover has a profound effect on frost depth as shown in, e.g., Williams and Smith (1989), Stähli and Jansson (1998), Kennedy and Sharratt (1998), and Ling and Zhang (2004). However, with the exception of the convective heat transfer coefficient used in the laboratory part of the study, the present manuscript is entirely focused on the processes tak-