Importance of moisture transport, snow cover and soil freezing to ground temperature predictions

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SUMMARY:
Prediction of undisturbed ground temperature is important to simulation of buildings with significant earth contact. A numerical model for heat and moisture transfer in partially frozen soils has been developed and validated. In addition to modelling conduction heat transfer, model variations that include moisture transport, snow accumulation and melting, and soil freezing and thawing are investigated. The results are compared against experimental soil temperature measurements at depths of 0.5 and 1.0 m for three locations in the northern United States. Results demonstrate the relative importance of moisture transport, snow cover, and soil freezing.

1. Introduction

Prediction of ground temperature is an important part of the simulation of buildings with significant earth contact. Undisturbed ground temperatures are often used as boundary conditions for simulations of heat transfer between building foundations and the ground. Depending on the approach taken by the simulation, ground temperatures near the building foundation may also be explicitly calculated. For buildings utilizing ground source heat pump systems, undisturbed ground temperatures are also needed for analysis of the ground heat exchangers.

Besides simulations used for energy calculations, undisturbed ground temperatures are often needed for simple foundation heat loss calculations. Despite this, availability of ground temperature data for engineers is surprising limited. In the US, the most commonly used approach (Kusuda and Achenbach 1965) relies on two weather-related parameters: annual average undisturbed ground temperature and annual amplitude of surface temperature variation, both of which are read from very small maps. These maps can be traced back to research in the 1920s and 1950s. The two parameters (along with soil thermal diffusivity and a phase delay parameter) are then used with a simple (one-year period) harmonic relationship that has the amplitude decaying exponentially with depth. This formulation was presented by Kelvin in 1860 (Thomson 1862) with multiple harmonics. ISO 13370(2007) appears to use this same formulation but starts with a sinusoidal representation of the annual outdoor and indoor air temperatures. Then periodic heat transfer coefficients and phase lags that apply to the entire air-temperature-to-air-temperature problem are computed with empirical expressions. All of these approaches assume pure conduction heat transfer with uniform thermal properties and sinusoidal boundary conditions; they neglect moisture transport, freezing/thawing and snow cover.

The authors are currently investigating the possibility of predicting undisturbed ground temperatures using typical meteorological year (TMY)-type weather files. The number of locations for which TMY-type weather data is available is growing at a tremendous pace and it seems possible that this might be leveraged to provide better predictions of undisturbed ground temperature using a 1-dimensional finite difference model. This paper addresses the question of what level of detail is required for accurate predictions of undisturbed ground temperature during the heating season. The final utilization of such predictions could take a number of forms, including tabulated parameters for the Kusuda and Achenbach (1965) model or an improved model, of form yet to be determined. This paper does not extend as far as modelling of basement or slab heat losses; for recent works in these areas with comprehensive literature reviews, see Deru (2003) and Rantala (2005).

2. Simulation approach

2.1 Model description

Heat and mass transfer in the ground are modelled using an explicit finite difference method. The model takes weather data, such as ambient air temperature, precipitation, solar radiation, wind speed, and humidity, as input data and determines the transient soil temperature and moisture content throughout the soil profile. Although the problem may be analyzed with a one-dimensional code, we have adapted a two-dimensional code and use a rectangular grid system with uniform grid over the computation domain which is 5m in depth and 3 cm in width. In order to obtain reasonable accuracy, a 4×569 grid is used with cells that are 8.8 mm in length and width. In turn, to satisfy convergence conditions, time-steps on the order of a few seconds are required.

Besides conduction heat transfer, three additional phenomena are included incrementally, so that the sensitivity of the temperature prediction accuracy to the detail level of the model may be studied. These phenomena are snow accumulation, moisture transport, and freezing of soil. Our approaches for modelling each of these three phenomena are discussed briefly below.

The model of snow accumulation and melting has been adapted from the model developed by Liu (2005). This model was developed for use in bridge snow-melting applications and experimentally-validated against a hydronically-heated bridge deck. The model is quasi-one-dimensional and a full energy balance (including precipitation, solar radiation, convection, thermal radiation and conduction) is utilized. Seven surface conditions are identified by the model: dry, wet, dry snow, slush, snow and slush, solid ice, and hoarfrost. Accordingly, it is necessary for the model to deal with boundary conditions representative of a wide variety of weather conditions, not just those during snowfall; but the model does not include the effects of evapo-transpiration. For this study, in which we only look at November-April, we expect that evapo-transpiration will have a negligible effect on moisture transport and temperatures.

Modelling of moisture transport due to precipitation, evaporation and condensation at the surface, and temperature/moisture gradients in the soil is also added to the model. The moisture mass flux at the top surface depends on two factors proposed by Khatri (1984): (1) maximum absorption capacity of soil at top surface $S_{\max}$; (2) moisture mass flux due to precipitation, snowmelt and evaporation / condensation R_{total}. If R_{total} is less than $S_{\max}$, moisture mass flux due to precipitation, snowmelt and evaporation / condensation will flow into the soil. Else, $S_{\max}$ flows into the soil, and the mass flux $(R_{total} - S_{\max})$ is assumed to run off immediately.

We have used the approach proposed by Philip and De Vries (1957) to describe the moisture transport due to moisture gradients and temperature gradients in porous material. The impedance of ice has been taken into account in calculating hydraulic properties (Koren, et al. 1999; Shoop, et al. 1997).

For freezing and thawing of soil, the effective heat capacity method (Lamberg, et al. 2004) is adopted. In this method, the latent heat effect is expressed as a finite temperature dependent specific heat which varies over a small temperature range. For our work, the actual values of specific heat vary with moisture content, but freezing and thawing were assumed to occur between 0 and -0.5°C, as illustrated in Figure 1 for a soil with 19.6% moisture by volume.

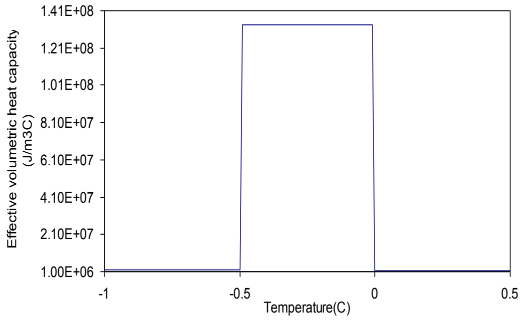


Fig.1 Efficient volumetric heat capacity

Additionally, the lower boundary condition is set with constant temperature and moisture. And the vertical boundaries of the domain are assumed adiabatic. The initial conditions are set by interpolating and extrapolating test data.

2.2 Model validation

We have validated the combined heat, moisture transfer and freezing models against measured data from laboratory freezing experiments performed by Jame and Norum (1976). A series of tests were performed with silica sandy soil placed in 300 mm long, 150 mm diameter cylinders with uniform initial temperatures (5°C) and soil water content. The model was compared to one particular experiment with a water content of 13.4% by volume and with the two ends of the column exposed to a cold plate set at -5.3°C and a warming plate controlled to 5.0°C.

A comparison between measured and simulated temperature and moisture distribution at 72 hours are shown in Figure 2. The model captured the phenomena of temperature and moisture distribution with adequate accuracy.

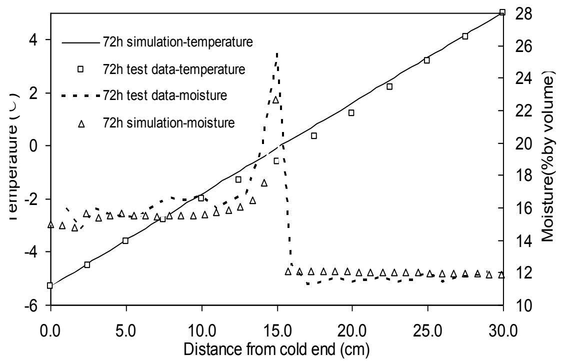


Fig .2 Comparison between simulation and observed results

2.3 Experimental measurement

The data used in the analysis were taken from the US Department of Agriculture's Soil Climate Analysis Network (SCAN). SCAN maintains monitoring stations throughout the US where soil temperature and moisture content are measured at several depths. Although some weather data are collected for all stations, many stations do not have precipitation measurements but three stations in Montana were located with complete weather data, including precipitation: Violett, Jordan, and Moccasin as shown in Figure 3. In this paper, temperatures are compared for two depths (0.5m, 1.0m).

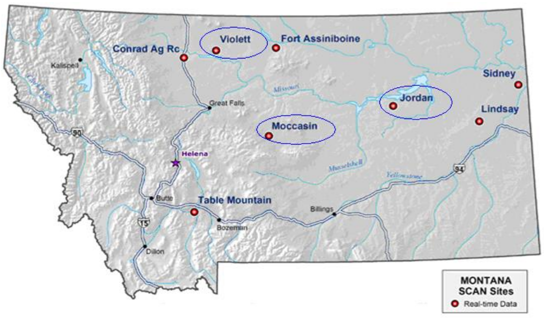


Fig.3 Experimental measurement sites (http://www.wcc.nrcs.usda.gov/scan/Montana/montana.html)

Cumulative precipitation at three locations during tested period (from the beginning of November to the end of April) is illustrated in Table 1. The precipitation is treated as rain (snow) when the ambient air temperature is higher (lower) than 0℃ in the model.

Table 1 Precipitation during test period

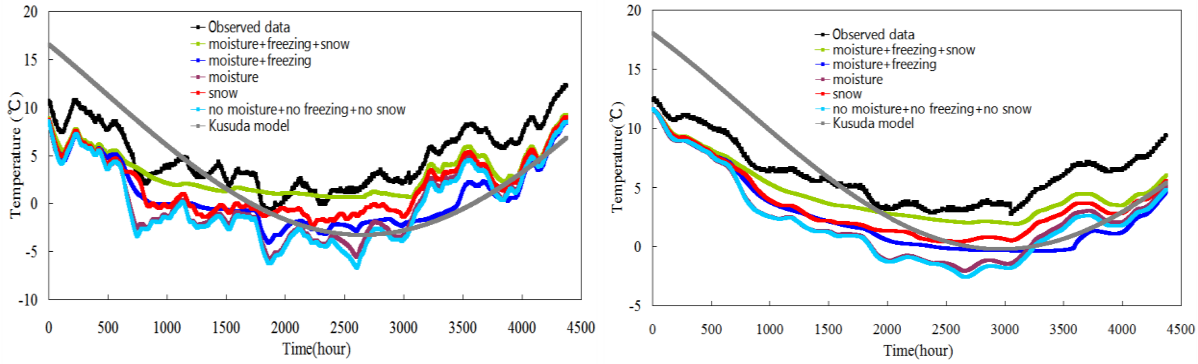
Location (Test period dates)	Rainfall(mm)	Snowfall in water equivalent(mm)	Total(mm)
Violett (2006.11-2007.4)	65	80	145
Jordan (2007.11-2008.4)	28	50	78
Moccasin (2006.11-2007.4)	62	78	140

Each SCAN station has extensively characterized layer-by-layer soil data. For each location, this soil data is used to estimate the soil thermal and hydraulic properties. Thermal conductivities are estimated using the Johansen model as summarized by Lu, et al. (2007) based on the soil bulk density, quartz content and moisture content. The first two parameters come from the on-site soil data; moisture content is computed by the model. Volumetric specific heat is determined with a volume weighted average of the values for dry soil, liquid water and ice. Saturated water content, residual water content, and the relationship between water content and soil matric potential are provided for each layer as part of the soil analysis. From the water content – soil matric potential relationship, we estimated the air entry tension and pore size/tortuosity parameter for each layer. The hydraulic conductivity is estimated from Rawls et al. (1982) based on the soil texture for each layer.

3. Results and discussion

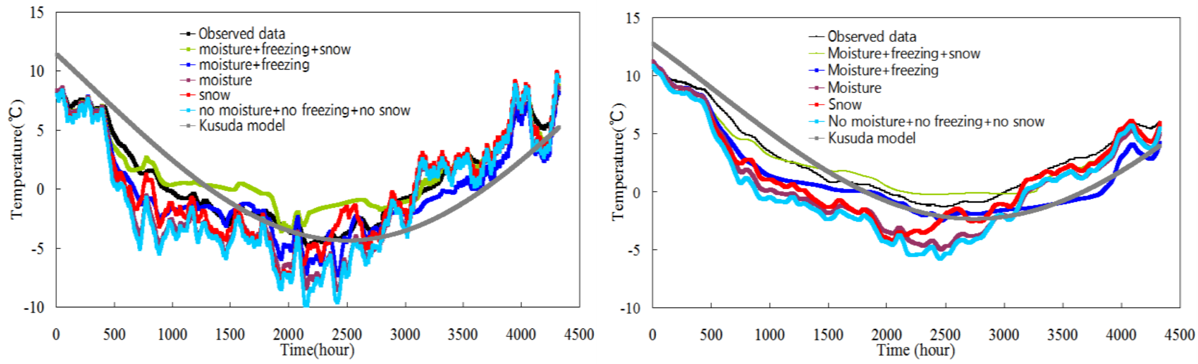
3.1 Sensitivity of the temperature prediction accuracy to the moisture transport, soil freezing, and snow cover

Results using the model with five combinations of modelled phenomena are compared to experimental measurements in order to determine the sensitivity of the temperature prediction accuracy to moisture transport, soil freezing, and snow cover. Figures 4-6 summarize the results. The legend for the figures may be explained as follows. All simulations include heat conduction. “moisture” indicates that the effects of moisture transport are included in the model but the effects of the freezing and thawing of soil and snow cover are excluded. “moisture + freezing” indicates that the effects of moisture and freezing/thawing of soil are included in the model but snow cover is excluded. “snow” indicates that only snow cover is taken into consideration. “moisture + freezing + snow” indicates that the effect of all three terms are taken into account in the model. “no moisture + no freezing + no snow” refers to the base model with only heat conduction. For cases where moisture is not modelled, the moisture content is set in terms of saturation percentage. For comparison purposes, the Kusuda and Achenbach (1965) predictions are also plotted.



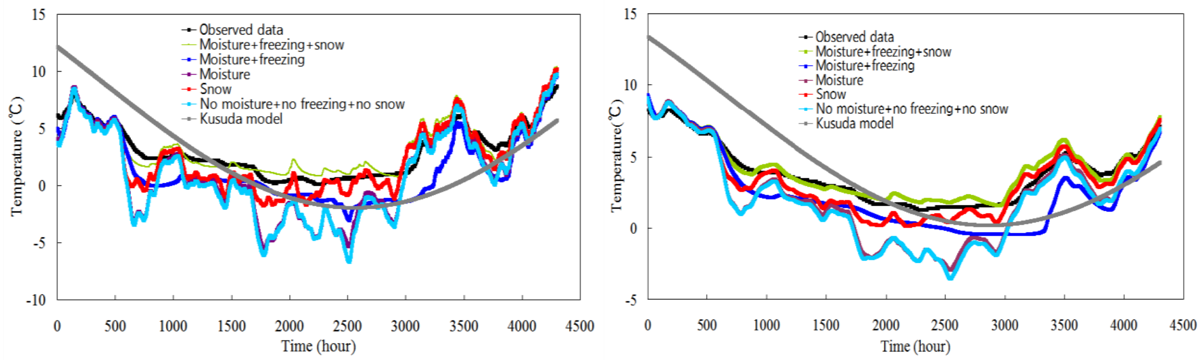
(a) 0.5m depth *(b) 1.0m depth*

Fig.4 Violett, Montana (2006.11~2007.4)



(a) 0.5m depth *(b) 1.0m depth*

Fig.5 Jordan, Montana (2007.11-2008.4)



(a) 0.5m depth *(b) 1.0m depth*

Fig.6 Moccasin, Montana (2006.11~2007.4)

In addition, RMSE is summarized for each model combination and depth/location in Table 2. For cases where moisture transport is not modelled, the moisture content of the soil used for the simulation is expressed as a percentage of saturation.

Reviewing the plots, several general observations may be made. First, especially for Violett, but for all sites, the comparison between the model and the results will not compare favourably to what might be achieved in a laboratory experiment with well-characterized thermal properties and boundary conditions. Nevertheless, since real buildings are built in real heterogeneous earth with real boundary conditions, this level of accuracy may be close to what might be achieved with a complete set of weather data, including precipitation. For building simulation applications, the level of accuracy shown here is likely acceptable for many types of buildings.

Table 2 RMSE of observed and simulated variables based on n number of sample

Model features				CPU time, min	0.5m, ℃			1.0m, ℃		
Moisture	Freezing	Snow	Saturation		Violett	Jordan	Moccasin	Violett	Jordan	Moccasin
×	×	×	0%	12	5.1	2.7	2.8	4.4	3.0	2.3
√	×	×	−	139	4.7	2.3	2.6	4.2	2.4	2.1
×	×	√	0%	16	3.1	1.8	1.3	2.7	1.9	0.9
√	√	×	−	146	4.4	1.5	1.9	3.7	2.0	1.7
√	√	√	−	167	1.9	1.4	0.8	1.5	0.7	0.5
×	√	×	0%	18	5.1	2.7	2.8	4.4	3.0	2.3
×	√	×	20%		4.3	1.6	2.2	3.8	2.0	1.9
×	√	×	40%		4.2	1.5	2.2	3.7	1.8	1.9
×	√	×	60%		4.3	1.7	1.8	3.6	1.7	1.5
×	√	×	80%		3.9	1.8	1.8	3.3	1.6	1.5
×	√	×	100%		3.9	2.3	1.7	3.3	1.3	1.4
×	√	√	0%	19	3.1	1.8	1.3	2.7	1.9	0.9
×	√	√	20%		2.5	1.2	0.9	2.3	1.0	0.5
×	√	√	40%		2.3	1.6	0.8	2.1	1.1	0.5
×	√	√	60%		2.1	2.0	0.6	2.0	1.2	0.4
×	√	√	80%		2.0	2.1	0.8	1.9	1.3	0.5
×	√	√	100%		2.0	2.6	0.8	1.9	1.5	0.6
Kusuda Model				−	4.6	2.3	2.9	3.2	1.9	2.4

More specifically, starting with the pure conduction cases ("no moisture + no freezing + no snow") the RMSEs for the six different cases range between 2.7°C and 5.1°C and as may be readily observed in Figures 4-6, the predicted temperatures are uniformly lower than the actual temperatures. This can be attributed due to two phenomena not modelled here:

1. Freezing and thawing of the soil. When there is a moderate amount of water in the soil- around 60-80% of fully-saturated conditions, freezing of the water in the soil reduces penetration of the low temperatures below the freezing front. Comparing the "60% and 80% freezing only" cases to the pure conduction cases, the RMSE is reduced between 20% and 50% by including the effect of freezing.
2. Snow cover. Once snow covers the ground surface, it forms an insulating layer and the ground below will stay warmer than if the snow were not to accumulate. Comparing adding only the snow cover to the pure conduction cases, the RMSE is reduced between 30%-65%

Furthermore, combining freezing (60% or 80% of saturation) with snow cover gives reductions in RMSE between 50% and 80%.

What about moisture transport? By itself, it only reduces RMSE from the base case between 0% and 20%, so it seems somewhat less significant that either freezing or snow. Including all three phenomena gives the best overall results, reducing RMSE by 60%-80%. However, the improvement is only slightly better than that gained by adding freezing and snow without moisture transport.

There are two additional considerations when choosing the combination of phenomena to model:

1. Computational time requirements. The required CPU time for each combination is summarized in Table 2. The CPU used for the test was an Intel Intel I5 2.81GHz processor.

Accounting for snow cover, freezing, or both snow cover and freezing results in a relatively modest increase in CPU time. However, accounting for moisture transport results in an order of magnitude increase in computational time. Given the relatively modest improvement in accuracy, the computational time may not be justified.

2. Availability of input data. In order to support modelling of moisture transport or snow cover, precipitation data are needed. For this study, we used precipitation data measured at the soil measurement site. However, for more general application of the model in conjunction with simulation of buildings or ground heat exchangers, typical meteorological year files, like TMT-3 files are commonly used. TMY-3 weather files have fields for precipitation data, but our cursory review of a few dozen sites did not identify any with precipitation data. At present, this will limit application of modelling of snow cover. It may be possible to augment TMY-3 weather data with monthly precipitation data and roughly estimate snow cover.

3.2 Selection of equivalent moisture content

From Table 2, it is clear that if moisture is not to be modelled, the assumed water content of the soil will have an effect on the accuracy of the results. To examine the sensitivity of the results to the assumed water content, six levels of saturation percentage between 0% and 100% were examined.

Six moisture contents were used for 3 locations under both “freezing + snow” and “freezing” conditions (the modes ignore moisture transport). Examining the RMSE for the “freezing-only” cases shows that there is significant improvement going from 0%-60% and there is relatively little change beyond that. For the “freezing + snow” cases, there is significant improvement going from 0%-20% and relatively little beyond that. Based on the limited number of sites examined, it is difficult to make a general recommendation, but a value in the range of 60% would be a reasonable estimate based on our present limited knowledge.

4. Conclusions

A two-dimensional numerical model for heat and moisture transfer in partially frozen soils has been developed. Given weather data, this model can predict temperatures and moisture contents in undisturbed ground. An effective heat capacity method is used to simulate freezing and thawing and a snow cover model has been adopted from previous work on pavement snow melting systems. The moisture transport aspect of the model is validated against Jame and Norum (1978). Various combinations of modelling of heat conduction, moisture transport, snow cover, and freezing/ thawing were evaluated against experimental data collected at three sites in Montana.

Conclusions for this work are as follows:

(1) For use in simulation of buildings and ground heat exchangers, the approach of modelling the soil with a surface energy balance, utilizing typical meteorological year weather data seems to be a feasible alternative to the Kusuda and Achenbach (1965) model which is limited by the availability of data. Here, only actual weather data for the period in question were used, so the ultimate accuracy for design purposes will depend on the degree to which the TMY-type data are representative of long-term weather conditions.

(2) If hourly precipitation data are not available, inclusion of freezing assuming soil that is 60% saturated gives RMSE no higher than 3.6℃ compared to hourly measured values over the heating season. If hourly precipitation data are available, inclusion of freezing and snow cover in the model RMSE of less than 2℃ for most cases. A procedure for using monthly precipitation data might allow rough accounting for snow cover in cases where hourly values are not available.

(3) Inclusion of moisture transport gives slight improvement in temperature predictions at the cost of an order of magnitude increase in computational time.

Finally, this study had a couple limitations that should be noted:

(1) Only three locations, all with fine grained soils in the northern US were investigated. Locations with other climate types and soil types should be investigated, pending identification of suitably complete data sets.

(2) Only green-field-type sites have been investigated. Procedures for urban environments are needed.

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