GeoStudio Example File

Effect of Snow Depth on Frost Propagation

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Introduction

Spatial variations in snow depth can have a considerable effect on the balance of energy at the ground surface, which ultimately governs the thermal response of the ground. The snow cover acts like an insulator during the winter months, dampening the geothermal response of the ground surface to significant changes in climatic conditions such as air temperature and wind speed. Due to the prevailing wind direction and topographic features of a site, the depth of snow can vary considerably. This example explores the effect of different snow depths accumulated on either side of a road embankment.

Background

Details of the surface energy balance (SEB) boundary condition can be found in the engineering book. The SEB is formulated based on the surface energy balance equation. The equation is written as follows when snow is covering the ground surface:

$$0 = -\left(q_{ns} - q_{nl}\right) + q_{sens} + q_{lat} + q_{snow} \qquad \text{Equation 1}$$

The sensible heat flux and net longwave radiation are calculated using the temperature at the top of the snow cover, and not the ground temperature. The energy flux through the snow is given by:

$$q_{snow} = -k_{snow}\frac{\left(T_g - T_s\right)}{D_s} \qquad \text{Equation 2}$$

where k_{snow} is the thermal conductivity of the snow, T_s is the temperature at the snow surface, T_g is the temperature at the ground surface, and D_s is the snow depth. Snow has a much lower thermal conductivity than soil, and thus acts as an insulating layer on the ground surface. Similarly, an increase in snow depth decreases the heat flux through the snow cover, which reduces the amount of heat injected or extracted from the ground.

Numerical Simulation

The model domain comprises a road embankment overlying a silt foundation. The roadway consists of 0.15 m of asphalt on 0.25 m of gravel. It must be noted that the thermal conductivity of the asphalt and gravel are lower than that of the silt material. The in situ volumetric water content of the asphalt, gravel, and silt is 0.02, 0.1, and 0.4, respectively. The initial temperature is defined using an arbitrary spatial function.

There are three SEB boundary conditions applied to the domain. Each boundary condition uses the same air temperature, wind speed, and incoming solar radiation functions. For the sake of comparison, the albedo is assumed to be the same on all three boundaries. The SEB boundary condition applied to the road surface does not include snow depth, evaporation, or vegetation functions. The SEB boundary condition applied to the left and right-hand sides of the embankment use the same vegetation height and evaporation functions, but different snow covers (left: 0.5 m, right: 0.1 m). The thermal conductivity of the snow is assumed equal to 10.45 kJ/day/m/°C. Although the temperature at the bottom boundary was assumed constant for illustrative purposes, a geothermal heat flux would have been a more realistic boundary condition.

The analysis starts on Day 250 and is solved for 100 days using 4-hour timesteps. To reduce file size, the duration is set equal to 10 days and the results are saved at every 6th timestep.

Results and Discussion

Figure 1 presents the temperature at the road surface as well as the ground surface on the left and right-hand sides of the embankment. The surface temperature starts at 10°C and warms rapidly to over 15°C. The temperature of the road surface is greater than that of the natural ground surfaces during the first forty-five days of the analysis due to climate and material properties. The lack of evaporative flux along the road surface results in larger positive heat fluxes, or heat influx, given that the incoming net radiation is unbalanced by the outgoing latent heat flux. In addition, the lower thermal conductivity of the asphalt and gravel yields a greater temperature increase for a given ground heat flux because a larger gradient is required to conduct heat into the ground. The specific heat capacity of all materials is the same, and therefore does not contribute to the differences in temperature response.

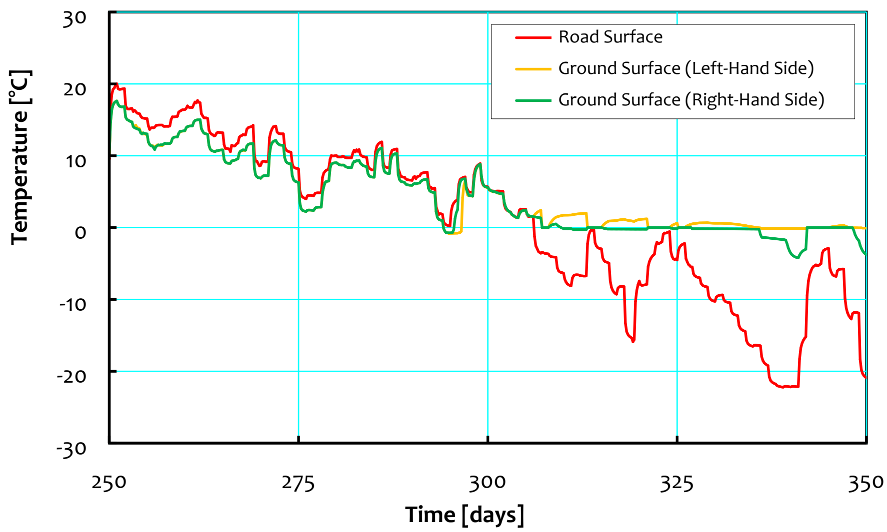

Figure 1. Ground surface temperature at three locations.

The daily air temperatures begin to drop below 0°C around Day 306. The road surface undergoes significant cooling/freezing over the winter months with the temperatures exhibiting significant variability in response to changing climatic conditions. In contrast, the thermal response of the ground surface is moderated beneath the snow cover. The snow protects the ground surface from the diurnal fluctuations in climatic conditions. Moreover, the ground surface on the left-hand side of the embankment, which has a 0.5 m snow cover, freezes at the surface over a short duration and the freezing front penetrates to negligible depth. The insulating effect of the snow cover in combination with the upwards heat flux prevents significant phase change. The ground surface on the right-hand side, with 0.1 m of snow cover, does freeze around Day 335.

The depth of the freezing front is in keeping with the thermal response of the different surfaces. Figure 2 shows very little frost penetration on the left-hand side of the embankment and approximately 0.25 meters on the right-hand side of the embankment. Figure 3 shows slightly more frost penetration, approximately 0.9 meters, beneath the road surface. The simulated response approximates the physical system reasonably well despite the snow cover being a single-step function, which results in instantaneous snow accumulation. The analysis clearly reveals the significant effect of snow cover on the thermal response of the ground.

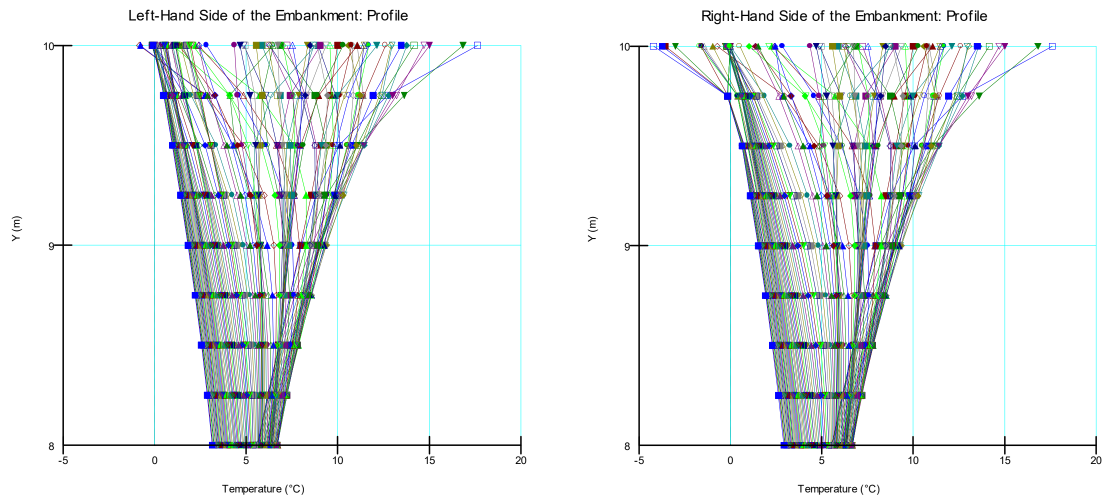

Figure 2. Temperature profiles on the left and right-hand sides of the embankment.

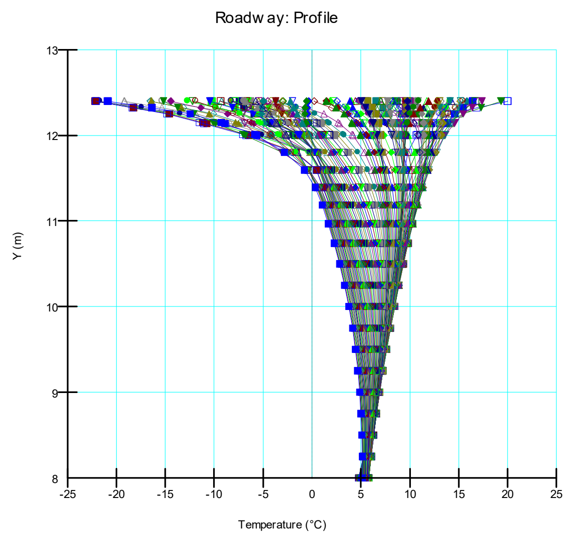

Figure 3. Temperature profile beneath the roadway.

Summary and Conclusions

This example demonstrates the effect of variations in snow cover thickness on the thermal response of the ground. Ground temperatures were found to be much more dynamic beneath the road surface compared to the left and right-hand sides of the embankment, which were insulated by 0.5 and 0.1 meters of snow, respectively. The frost depth was also found to be much more significant beneath the roadway.