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GeoStudio Example File
Surface Energy Balance

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Introduction

There are many problems in geotechnical engineering that involve coupling between climatic conditions and thermal ground response. In the literature, these types of problems are often referred to as land-climate interaction or soil-vegetation-atmosphere (SVA) interaction problems. Some examples include the protection of permafrost in northern regions, the design of near-surface geothermal energy systems, design and construction of frozen capillary barrier cover systems, and the design of foundation insulation in cold climate regions. In these cases, the thermal response within the ground is highly dependent on the atmospheric conditions, which in turn, are a function of the land surface conditions.

Engineering problems of this nature require a description of the energy transfers between the ground surface and the atmosphere, termed the surface energy balance. The global objective of this example is to describe and demonstrate the use of the surface energy balance (SEB) boundary condition implemented in TEMP/W. The specific objectives of this example include:

1. Highlighting the key climate and material inputs,
2. Demonstrating the insulating capacity of the snowpack on the thermal response of the ground during winter conditions, and
3. Demonstrating the numerical stability of the TEMP/W implementation for a SEB boundary condition.

Background

The amount of energy delivered to the earth's surface from the atmosphere is the net radiation, and more specifically, the difference between the net shortwave and net longwave radiation. This energy is utilized by several processes at the ground surface such as evapotranspiration, sublimation, changing the air temperature, and changing the soil temperature (heating or cooling the ground).

The energy conservation statement at the ground surface can be written as:

$$(q_{ns} - q_{nl}) = q_h + q_l + q_g$$ **Equation 1**

where

$(q_{ns} - q_{nl})$	is the net radiation [MJ/m^2/day^1]
q_{ns}	is the net solar (shortwave) radiation [MJ/m^2/day^1]
q_{nl}	is the net terrestrial (longwave) radiation [MJ/m^2/day^1]
q_h	is the sensible heat flux [MJ/m^2/day^1]
q_l	is the latent heat flux [MJ/m^2/day^1]
q_g	is the ground heat flux [MJ/m^2/day^1]

The terms in this equation are energy fluxes, which are defined as energy rates per unit surface area. Sellers' (1968) sign convention is adopted such that net radiation is positive downwards (toward the ground surface), latent and sensible heat fluxes are positive upwards (away from the ground surface), and ground heat flux is positive downward (into the ground). The equation states that all energy received at the earth's surface must be used to warm or cool the air above the ground surface (sensible heat flux), evaporate water (latent heat flux), or then again, warm or cool the ground (ground heat flux). Details of the individual energy flux terms are presented in the Engineering Book.

In an analysis involving climate interaction, the thermal response within the domain is primarily controlled by the ground heat flux. A positive ground heat flux implies energy input into the ground, while a negative ground heat flux indicates energy extraction. Equation 1 is therefore solved for the ground heat flux as:

$$q_g = (q_{ns} - q_{nl}) - q_h - q_l$$ Equation 2

The ground heat flux is solved as the residual of the energy balance equation and applied as the boundary condition on the finite element domain. The surface energy balance equation can be re-written to accommodate for the presence of snow during the winter months:

$$q_{snow} = q_g = (q_{ns} - q_{nl}) - q_h - q_l$$ Equation 3

where the energy flux through the snow, q_{snow}, is assumed equal to q_g, which infers that the snow does not have the capacity to store energy.

It should be noted that the application of a flux boundary condition in a finite element analysis can often lead to numerical instability. The instantaneous flux calculated at the beginning of a time step can result in an excessive amount of energy being extracted or injected into the domain. In turn, the temperature of the ground is under or overestimated, resulting in a reversal of the flux rate on the subsequent time step. Eventually, the analysis becomes prone to numerical oscillation. The SEB boundary condition is implemented within TEMP/W in such a manner as to prevent this oscillation from occurring; thereby ensuring a numerically stable solution even with larger time steps.

Numerical Experiment

TEMP/W is used to model a case study presented by Hwang (1976). The objective of this example is to demonstrate the process of modeling a surface energy balance problem. It should be noted that TEMP/W implements different equations for surface energy balance components than those presented by Hwang (1976), particularly for calculating sensible heat flux and net longwave radiation. The results are therefore expected to differ from those found in the paper. It must be noted that no attempt is made to calibrate the model or replicate the original results.

The study site is located at Normal Wells, Northwest Territories, Canada (latitude 65.2° N). The major stratigraphic units comprise peat, silt, and till overlying a shale unit. The thermal properties of each unit are modelled using a simplified thermal material model, which assumes constant thermal conductivity and volumetric heat capacity for frozen and unfrozen conditions.

The climate data is scaled from the figures presented in the paper, entered into a spreadsheet, converted into the appropriate units, and then pasted into the boundary functions (see GSZ file). As in the original study, the snow conductivity is set equal to 0.00026 kJ/sec/m/°C, the evaporative flux is uniformly distributed throughout the year, and the summer and winter albedo is set equal to 0.15 and 0.75, respectively.

Results and Discussion

Figure 1 shows the simulated ground surface temperature response using 2, 12 and 24-hour timesteps. As expected, the results are similar regardless of the size of the timesteps. Although the air temperature drops below –30°C during the winter months (refer to Figure 2), the ground surface temperature varies between –10 and –15°C due to the insulating capacity of the snowpack, which dampens the ground heat flux. In this example, diurnal fluctuations in ground surface temperature are not captured due to the resolution of the climate data. This is particularly apparent in the incoming shortwave radiation, which is assumed constant over approximately 15-day intervals.

It must be noted that the duration of the analysis in the associated GeoStudio file is set equal to 30 days to minimize file size.

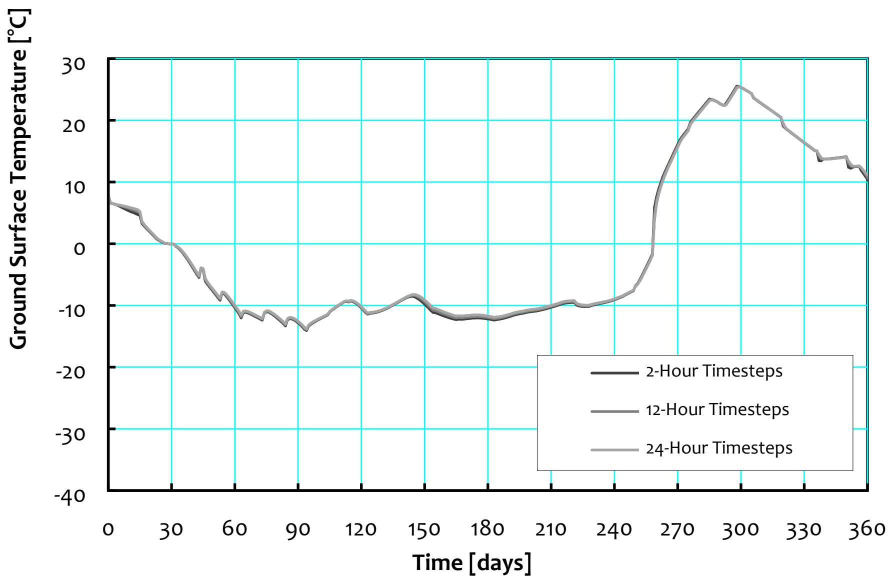

Figure 1. Ground surface temperature response for three different time steps.

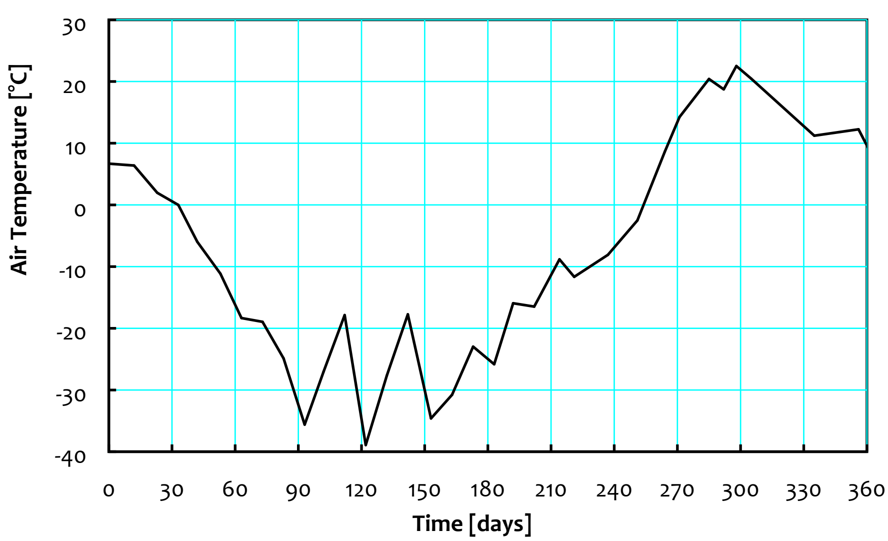

Figure 2. Air temperature.

Figure 3 compares the simulated ground surface temperature response to that at various depths. The cooling and warming trends are delayed and dampened at depth relative to the response at the ground surface. The temperature at one-third of a meter below ground surface hovers around the freezing point temperature as latent heat is released from the soil between day 40 and day 50 whereas the temperature at a depth of one-meter hovers at the freezing point temperature between day 50 and day 80. The delay is more pronounced at depth because of the increasingly smaller thermal gradients in the active region and the decreasing (less negative) ground surface heat extraction rate caused by snow accumulation (refer to Figure 4). The rapid increase in ground temperatures, at day 258, coincides with the large spike in heat injection rate brought on by warmer air temperatures. The results are in favorable agreement with in-situ measurements.

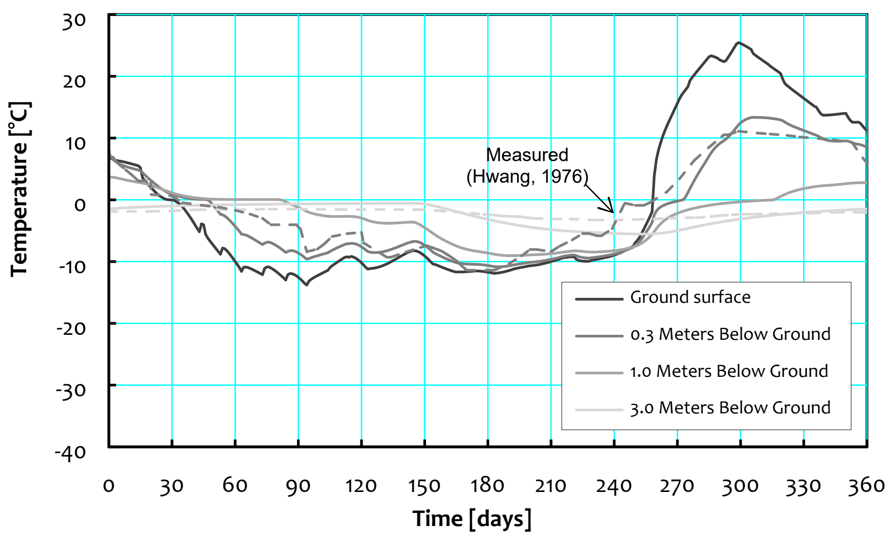

Figure 3. Ground temperature response at 0.3 m, 1.0 m, and 3.0 m below ground (24-hour timesteps).

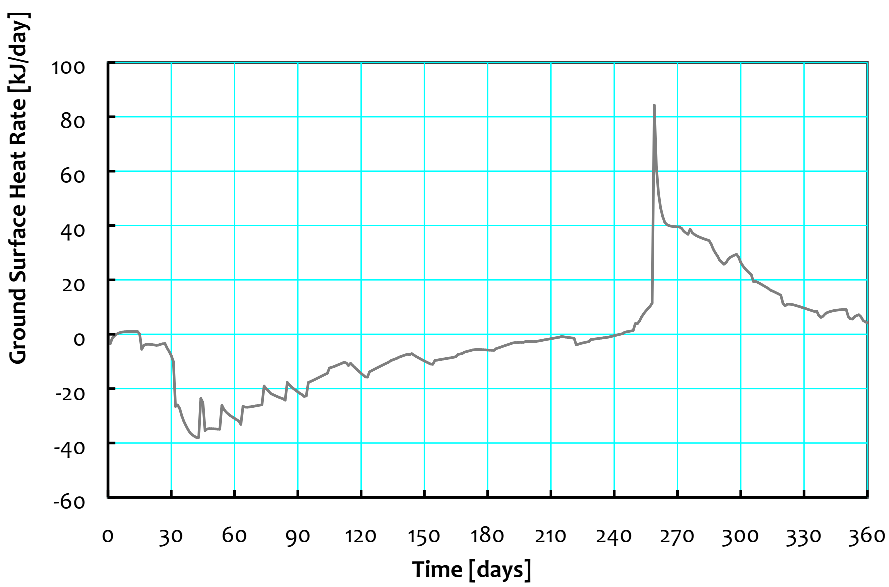

Figure 4. Ground surface heat rate (24-hour timesteps).

Summary and Conclusions

The surface energy balance boundary condition in TEMP/W was used to model the coupled response between the ground and atmosphere. The boundary condition inputs included: air temperature, wind speed, radiation, evaporation height, and snow depth. The inputs were used to calculate the key components of the surface energy balance, which was ultimately used to compute the ground heat flux at a study site located at Normal Wells, Northwest Territories, Canada.

The results were found to be in favorable agreement with in-situ measurements and Hwang's (1976) predictions. The results also demonstrated the dampening effect of the snow cover on ground temperature fluctuations as well as the stability of the boundary condition implementation when using large timesteps.

References

Hwang, C.T. 1976. Predictions and observations on the behaviour of a warm gas pipeline on permafrost. Canadian Geotechnical Journal, 13(4): 452 – 480.

Sellers, W.D. 1965. Physical Climatology. University of Chicago Press. Chicago, Illinois.