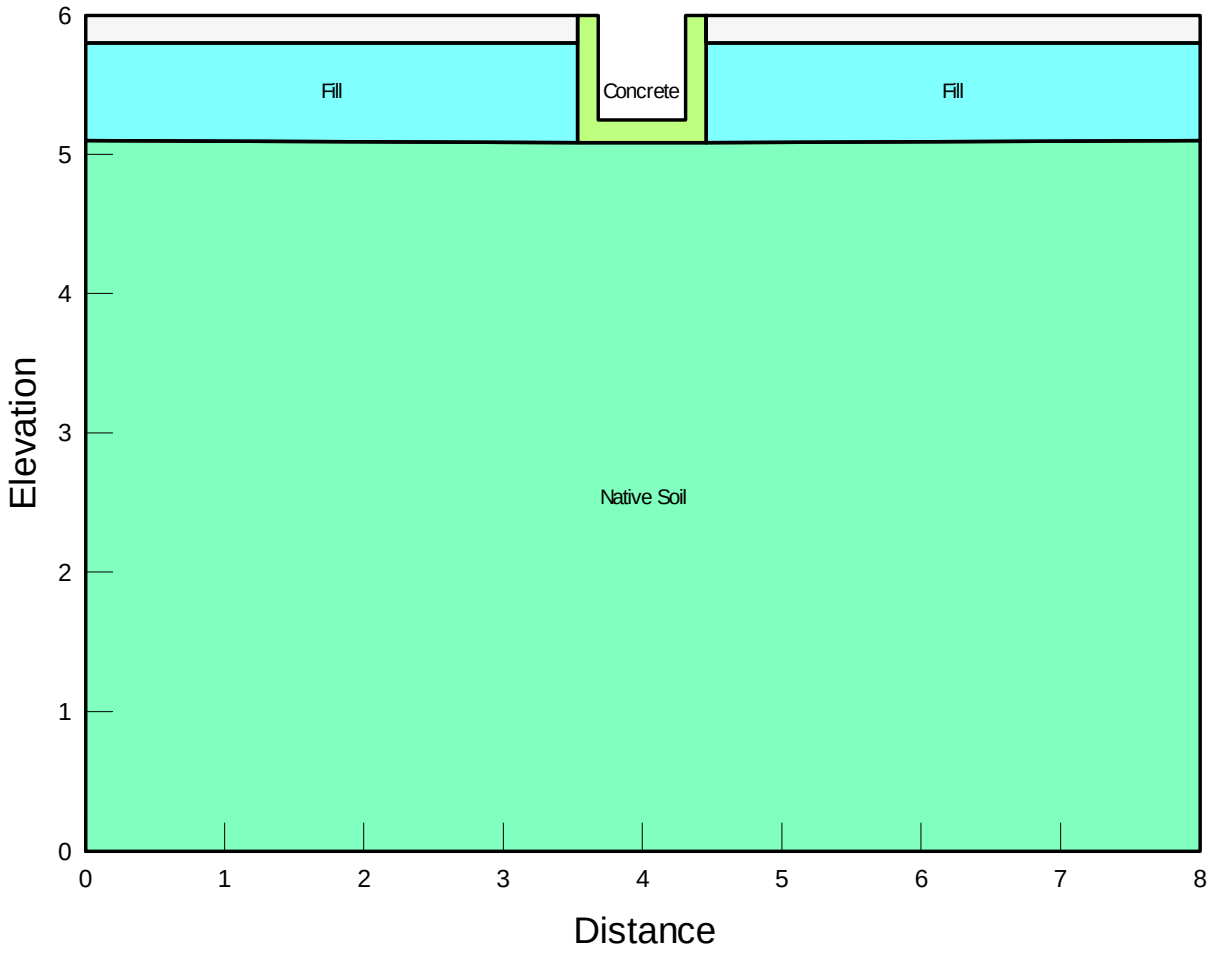
Frost beneath Exposed Culvert

1 Introduction

The objective of this analysis is to estimate the frost penetration beneath an exposed concrete culvert that is exposed to an average air temperature of -8.5 C over a period of two months. Two cases are considered: no snow cover, or 200mm snow cover. It is a simplified abstraction of a complex process linking ground thermal profiles to climate data.

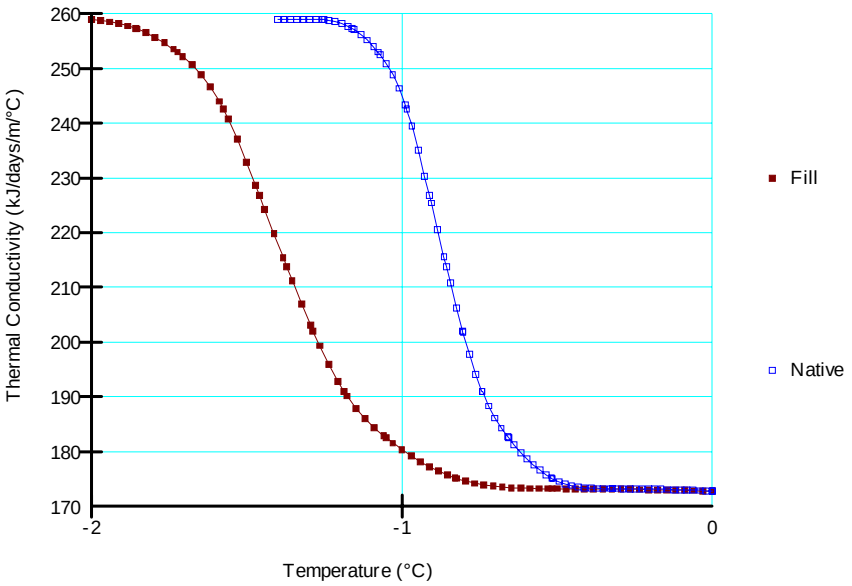
2 Geometry and boundary conditions

The geometry for this analysis is shown in the image below. Six meters of profile is modeled with the top 200mm being set as snow pack for one of the two modeled cases. A 150mm thick concrete culvert is placed near the ground surface and extends to just over 700mm from the ground surface. The near surface soil is a silty sand fill material that sits on a sandy native soil material. The local water table sits about 90mm below the contact of the fill and native soil. In this model it is assumed the water content in this 90mm band is tension saturated and has the same value as the saturated sandy material below.

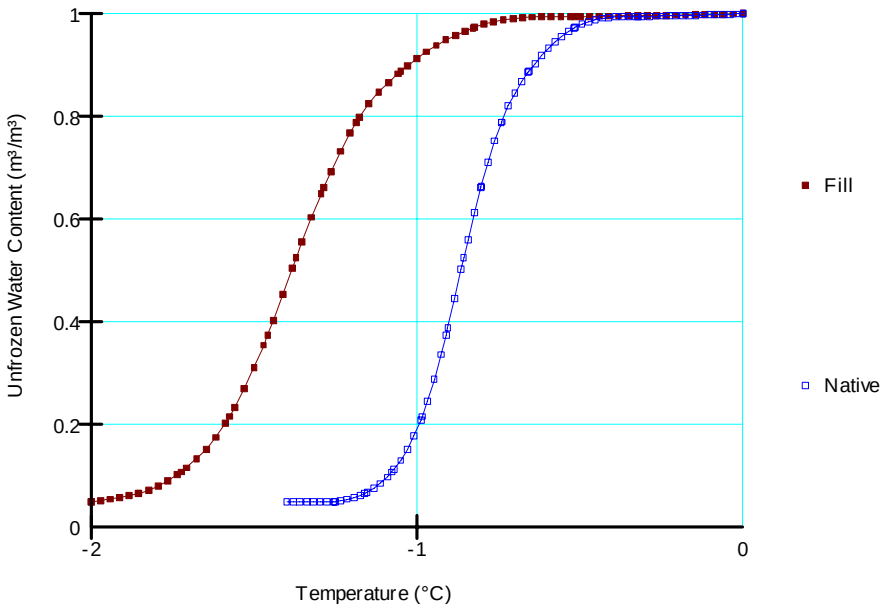


3 Material properties

There are four materials used in these analyses. The fill and native soil are represented using the conductive heat transfer model which assumes thermal conductivity varies as a function of soil temperature as shown below.



The unfrozen water content functions for these materials is shown next.



Both of the above functions show thermal properties that change over a narrow temperature range below the phase change point. This phenomenon is a result of capillary forces that hold the water in the void

space of soils. The finer the soil particle size, the wider the range of temperature that soil properties vary over as they transition from unfrozen to frozen values.

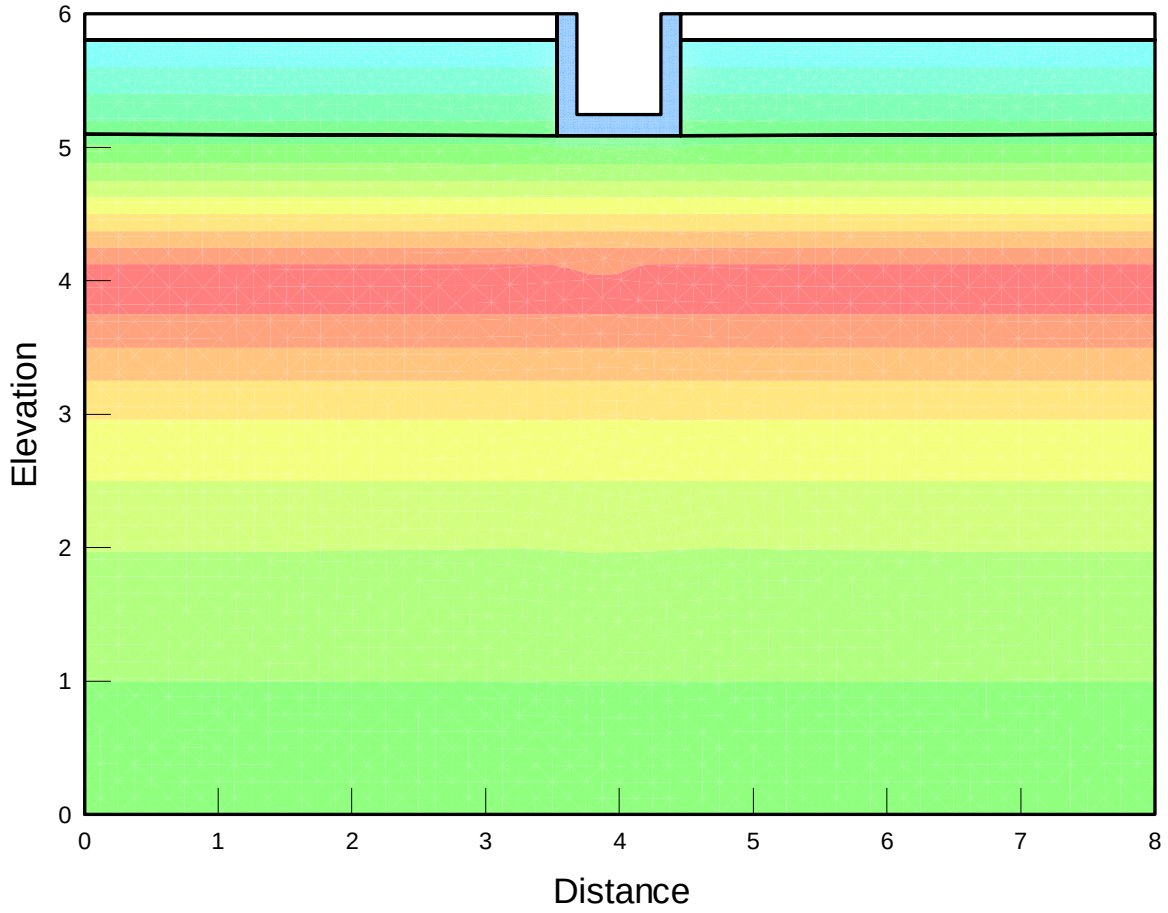
The water content for the fill material was assumed to be 18% by volume (12% by weight) and that of the native soil 40% by volume (30% by weight). The volumetric heat capacity of both soils were assumed to be 2700 kJ/m3/C for the unfrozen case and 2600 kJ/m3/C for the frozen case.

The concrete and snow were modeled using a simplified thermal model with constant thermal properties in the frozen and unfrozen states. In both cases the frozen and unfrozen values were set to be the same.

The snow was assumed to have a thermal conductivity of 31.1 kJ/day/m/C (0.36 W/m/K) with a heat capacity of 740 kJ/m3/C. The concrete thermal conductivity was set at 155.5 kJ/day/m/C (1.8 W/m/K) with a heat capacity of 2600 kJ/m3/C.

4 Initial and Boundary Conditions

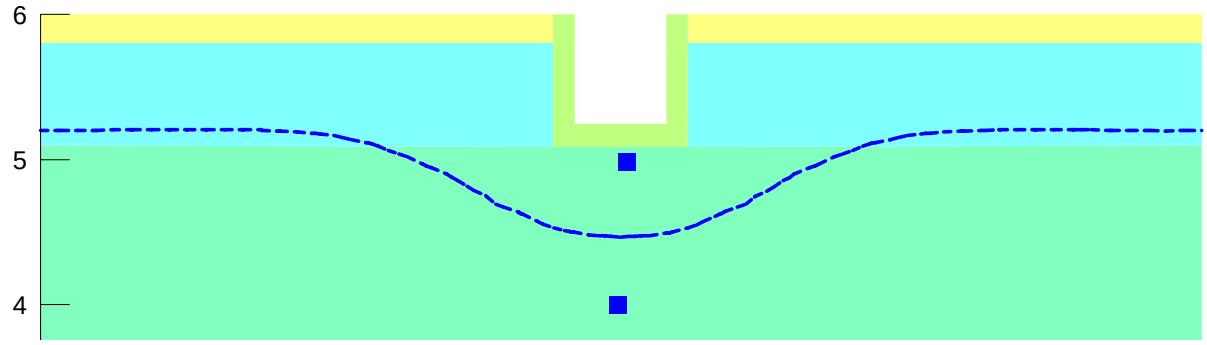
In order to model a transient case it is necessary to establish the initial condition (temperature) in the soil prior to application of the transient boundary conditions. In these analyses, a spatial function that varies temperature with elevation was applied. The spatial function assumed a temperature of 2.4 C near the surface, 9C at a depth of 2m, and 5C at the base of the model.



The bottom boundary condition for both analyses is set to a constant value of T= 5 C and the top temperature is set to be -8.5 C for the two month duration. The top temperature is applied to either the ground or snow surface as well as the internal walls of the exposed culvert.

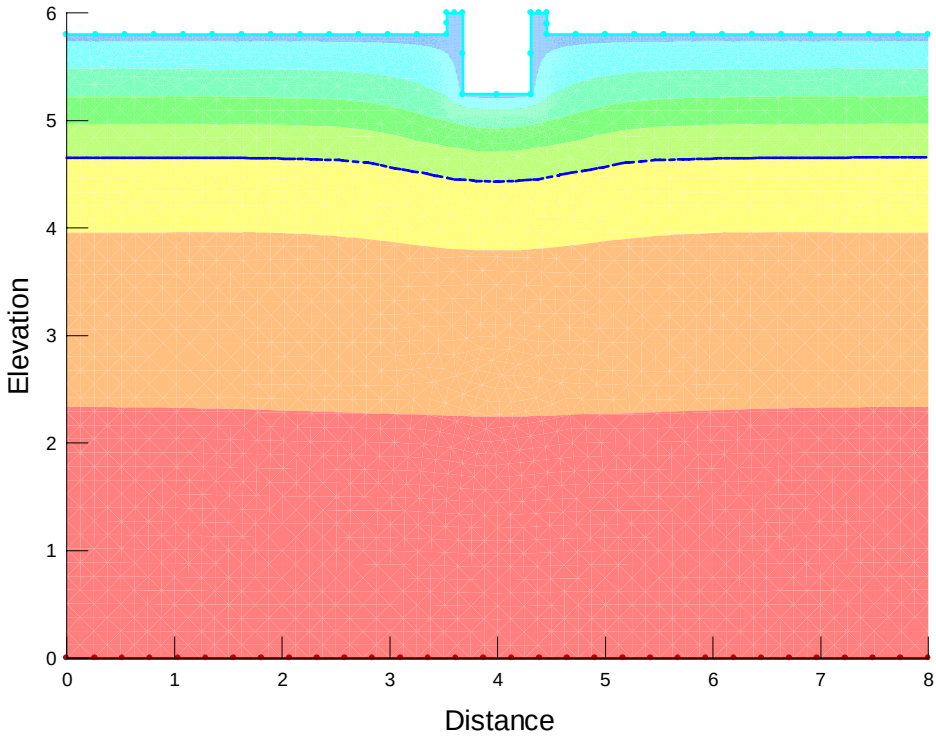
5 Discussion of results

Temperature contours with the freeze front will be shown for each case modeled. In addition, graphs of temperature change over time at locations 1m and 2m below the culvert top (as shown below) will be presented.

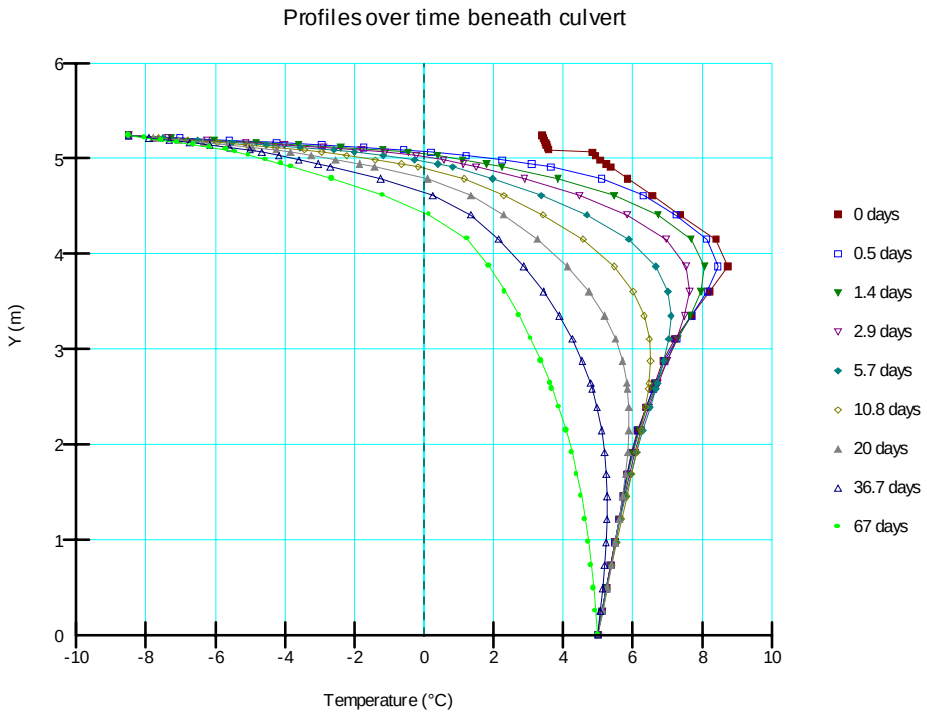


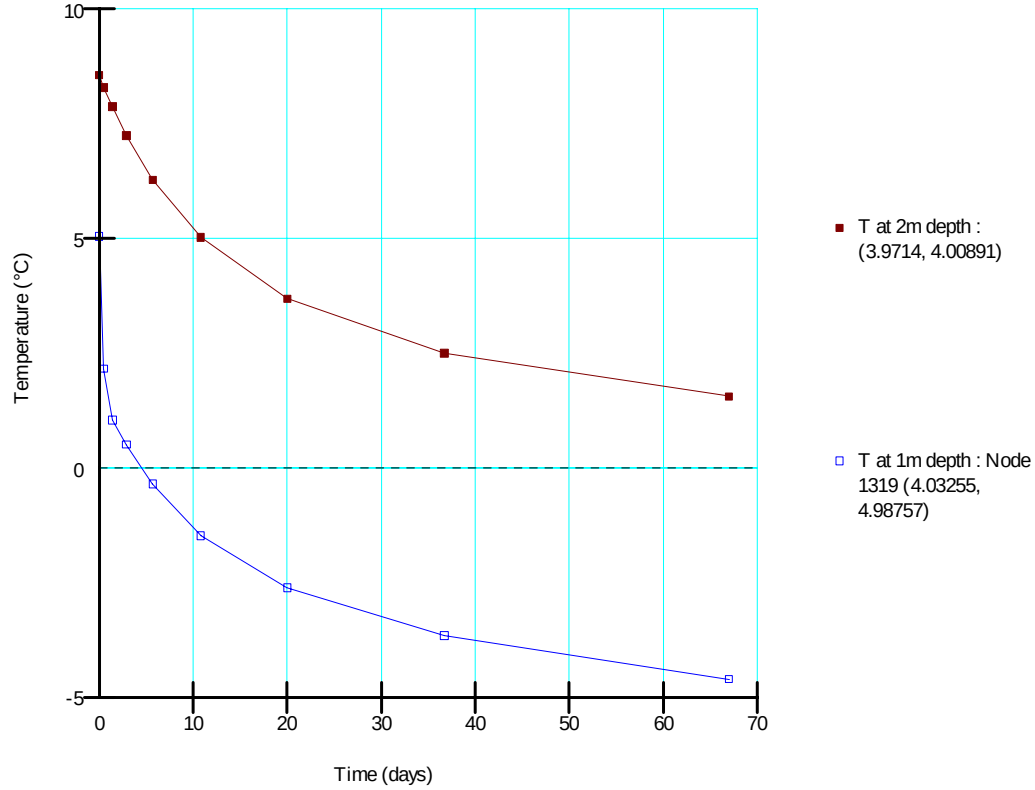
Case with no snow:

The location of the zero degree isotherm (frost line) after 67 days is shown below.

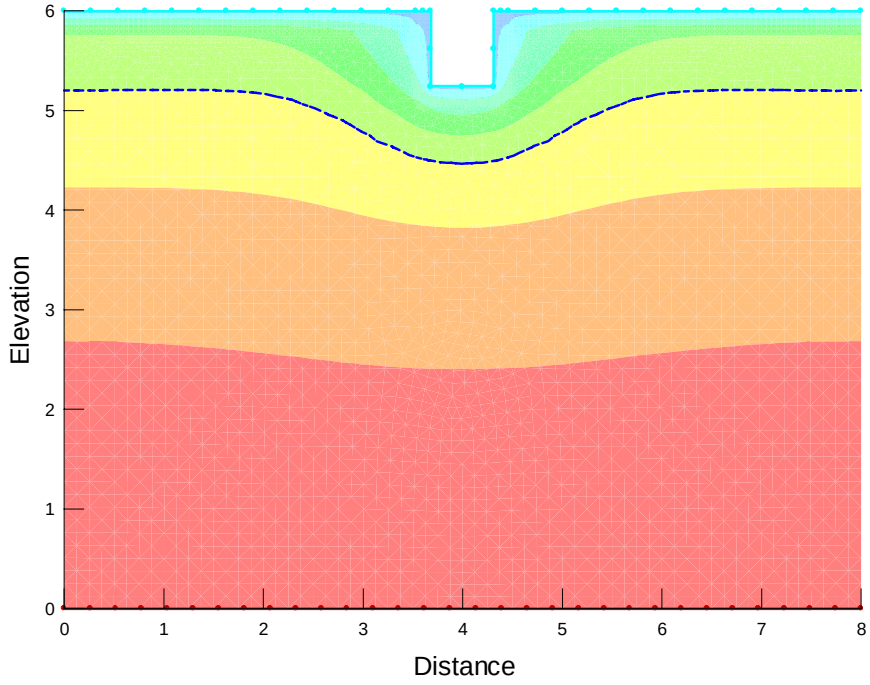


Temperature profiles taken at the mid point of the culvert at various times are given next. The temperatures begin at time 0 days with the applied initial condition profile and then cool off over the next 67 days.

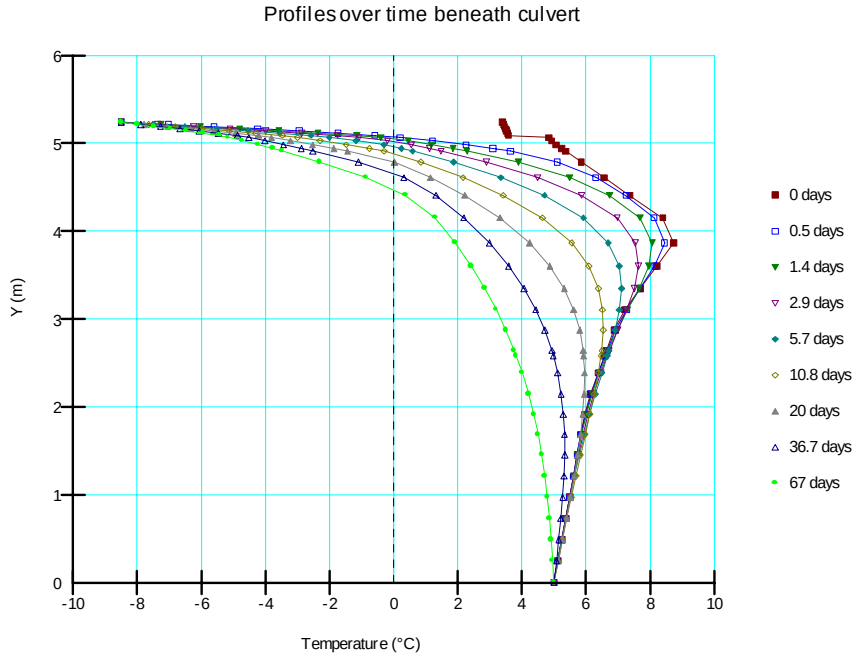

Profiles over time beneath culvert
Y (m)
Temperature (°C)
0 days
0.5 days
1.4 days
2.9 days
5.7 days
10.8 days
20 days
36.7 days
67 days

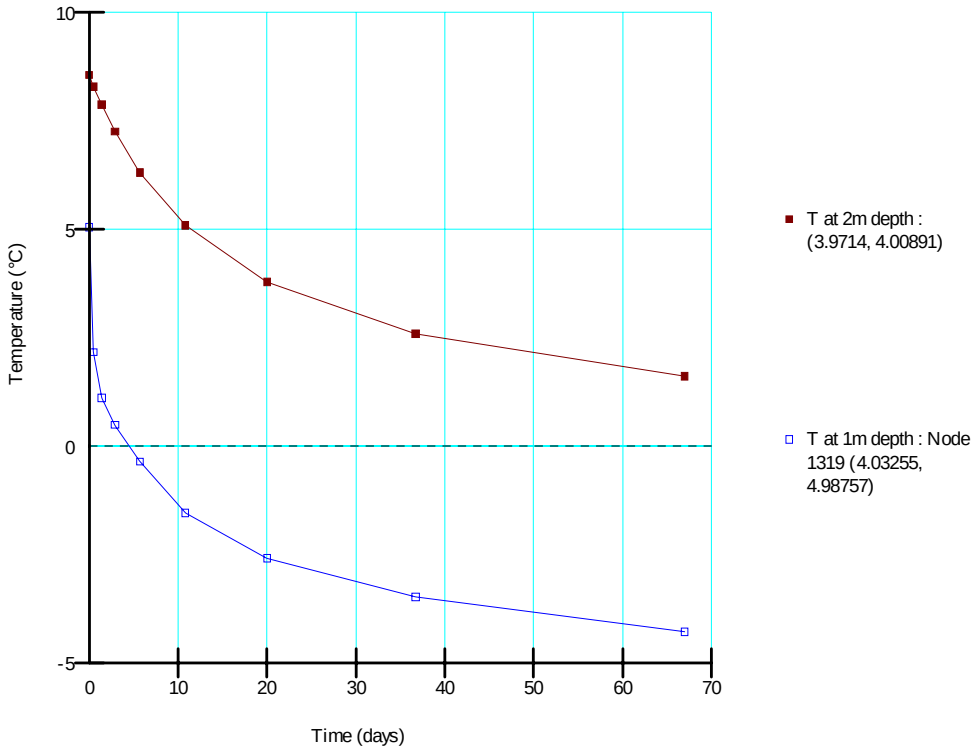

Temperature (°C)
Time (days)
T at 2m depth : (3.9714, 4.00891)
T at 1m depth : Node 1319 (4.03255, 4.98757)

Case with snow:



The freeze front for the case with a 200mm snow cover is shown above. The frost penetrates less beneath the open ground but almost the same beneath the exposed culvert. The temperature profiles over time for this case are given below.




10
5
0
-5
Temperature (°C)
0
10
20
30
40
50
60
70
Time (days)
T at 2m depth : (3.9714, 4.00891)
T at 1m depth : Node 1319 (4.03255, 4.98757)