

Freezing around a Pipe with Flowing Water

1 Introduction

Typically ground freezing modeling has ignored the fact that the presence of moving water can significantly change or even prevent freezing of pore-water. Modeling the coupled thermal-hydraulic process was introduced in GeoStudio in 2004. Enhancements to the implementation of this coupled analysis were added in GeoStudio 2007, with the introduction of a special “Coupled Convective Thermal” soil model in TEMP/W. This example discusses the coupled modeling of heat and water flow and compares solutions for heat conduction only, or both conduction and convection.

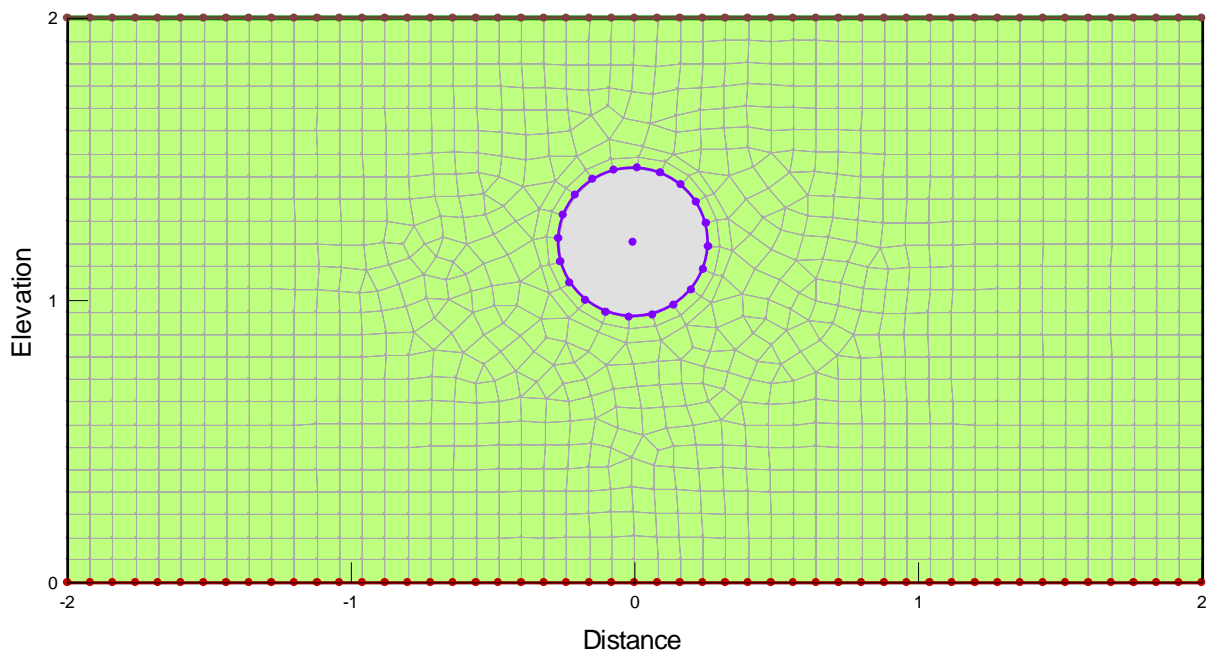
2 Feature highlights

GeoStudio feature highlights include:

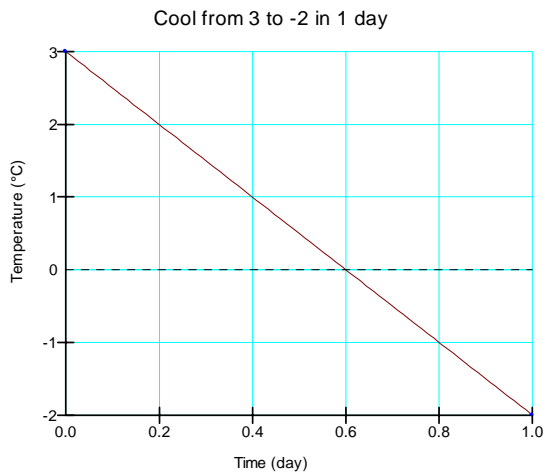
- Transient 2D freezing with and without moving water
- Convective heat transfer
- Coupling thermal and hydraulic analyses
- Multiple analyses in one file

3 Geometry and boundary conditions

When trying this coupled analysis for the first time, it is recommend that you start with a simple geometry such as the one shown below. In this example, a cold pipe will freeze soil pore-water around it. However, if there is a hydraulic gradient across the region, then the flowing water will change the rate at which the ground freezes. In this simple model, it is easy to hand calculate hydraulic gradients, so that flow velocities can be known.



The thermal boundary conditions at the top and bottom of the model are 3 degrees and 3.1 degrees, respectively. These are the same in the initial condition steady state analysis, as well as in the transient conduction and transient convective analyses. For the transient analyses, the pipe surface temperature is a function such that the pipe cools from a temperature of 3 to -2 over a 1 day period. Ramping a boundary function lessens any numerical shock on the system. The function is shown below.



The hydraulic boundary conditions are important in this model. If the ground is saturated, then the actual magnitude of heads in the soil are not important. It is very important though, that the head distribution across the domain produces the correct gradient, such that when multiplied by the conductivity, yields the estimated in-situ flow velocity. In this example, the heads on the left side are set at 3 m, and those on the right are 3.02 m. The model is 4 m across, so the gradient is $0.02 / 4 = 0.005$. When multiplied by the saturated conductivity of 150 m/day, this results in a velocity of 0.75 m/day from right to left.






This example has several analyses in it. Both the seepage and thermal transient models require a known starting condition. It is not acceptable to use the Water Table or Activation Pressure / Temperature options to start the transient models, because you need to confirm the flow gradients before you start the convective process. The transient models can then point to the steady state results for their initial conditions.

This example also contains a transient conduction analysis. This should be included always, so that you know what the solution is before you add the complexity of the convective analysis.

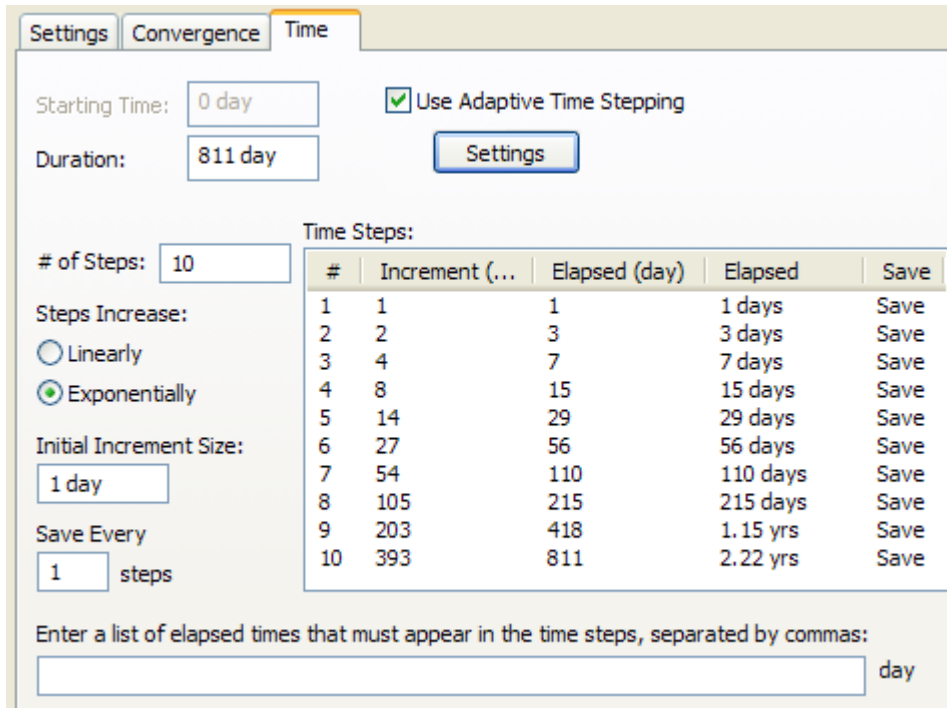
The image below shows the analyses in this example.

Analyses

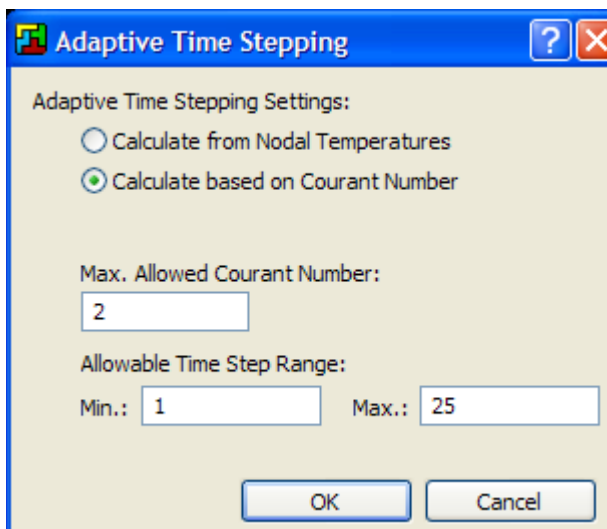
KeyIn Analyses:

-  **Insitu seepage** [Set up cross flow prior to freezing]
-  **2b - slave to temp cooling** [Will be a slave to TEMP/W and launched by TEMP/W solver.]
-  **Insitu thermal**
-  **1 - transient conduction only** [Not coupled with SEEP/W]
-  **2 - transient convective cooling** [Will be the master process and control the SEEP/W solver]

The transient models are set up to solve 811 days of time, as shown below. The time steps will increase exponentially and data will be saved at the end of each step.

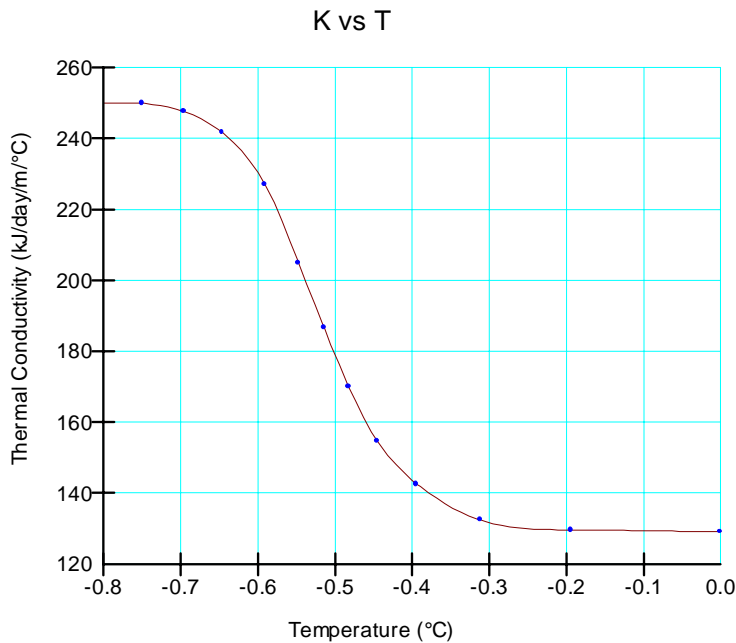


This elapsed time is divided into 10 time increments; however, the adaptive time stepping scheme has been enabled so that additional time steps are inserted into the user defined steps as necessary to maintain stability of the numerical solution. The adaptive scheme is set up to allow a minimum step of 1 day up to a maximum step of 25 days. The rate of change of time is controlled by the Courant Number criteria, which is discussed in more detail in the TEMP/W Engineering Methodology book.



4 Material properties

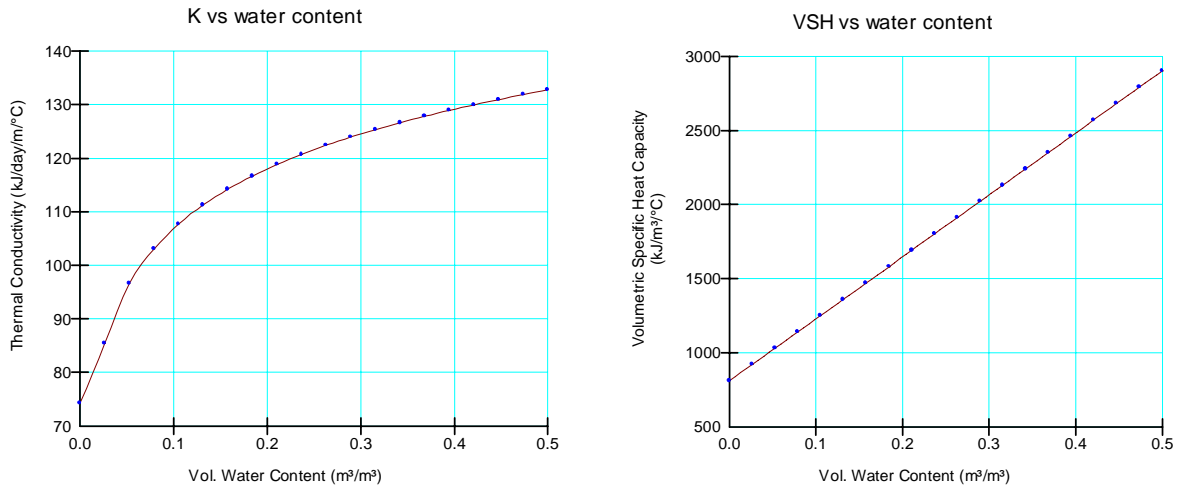
The material properties used in this type of analyses must be considered carefully. In a normal TEMP/W (conduction only) model, the thermal conductivity is input as functions of temperature such as shown below for this soil in the conduction only analysis.



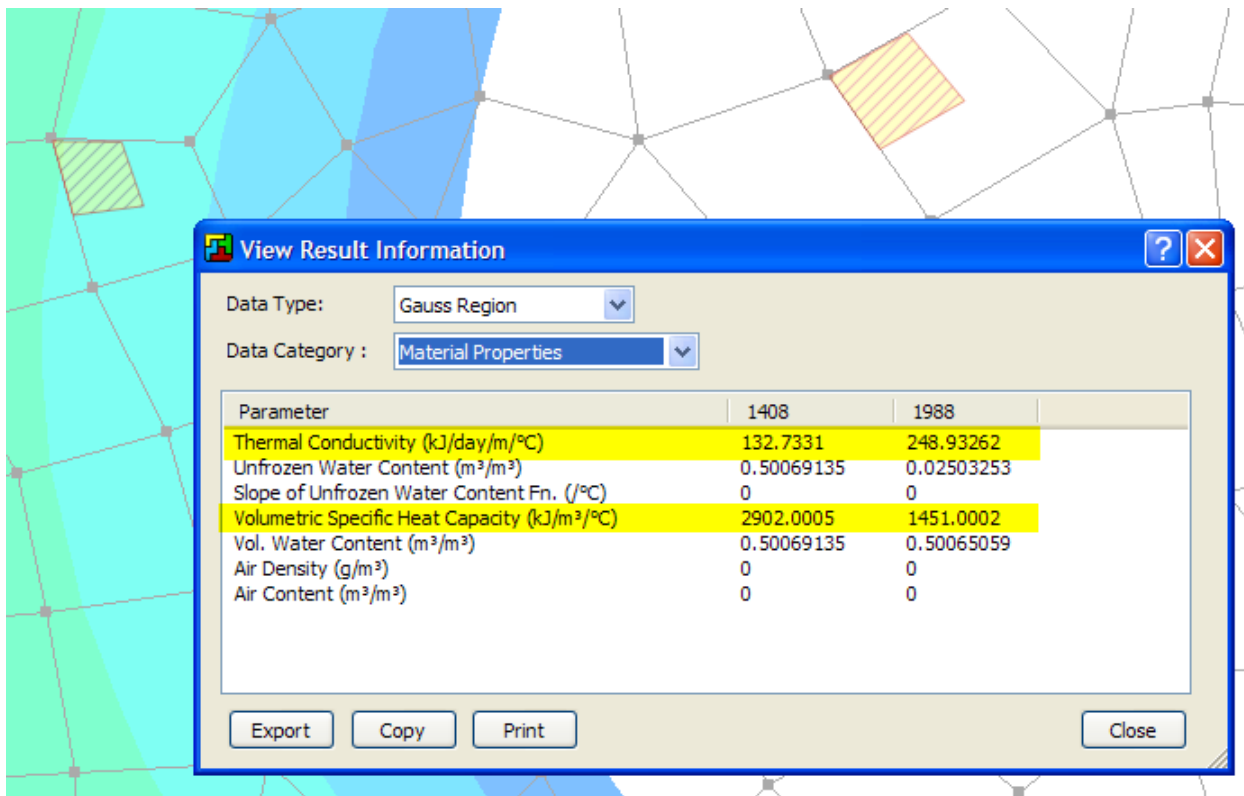
The volumetric heat capacity is set for the frozen and unfrozen cases and a fixed water content is applied as shown here.

Material Model:	Full Thermal	
Thermal K vs Temp. Fn:	K vs T	
Unfrozen Vol. WC Fn:	UWC for coarse soil	
Volumetric Heat Capacity:		
Unfrozen:	2900 kJ/m ³ /°C	Insitu Vol. Water Content: 0.5 m ³ /m ³
Frozen:	1450 kJ/m ³ /°C	<input type="checkbox"/> Activation Temp: 0 °C

In a convective heat transfer analysis, the above format for definition of soil properties will not work because it is possible that the water contents may change over time. For this reason, GeoStudio 2007 introduces a new Coupled Convective Thermal model in which the thermal conductivity and heat capacity values are functions of water content, as shown below.



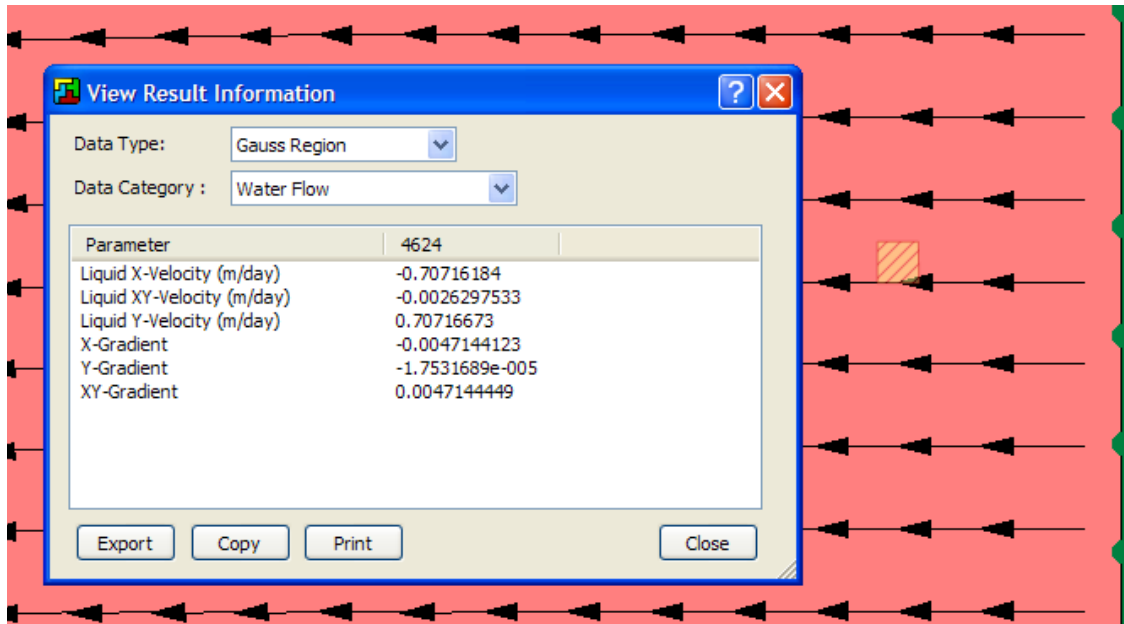
If you consider the difference between these functions and the conduction only TEMP/W functions, you will see that while these two functions let the thermal properties be known for varying water contents, they do not say anything about what happens when the water freezes. There are built in algorithms in the solver to use these functions and modify them if the actual water contents change to ice. If you need to see what the computed values are, you can use the View Results Information or Draw Graph options in CONTOUR to see what the computed values are, as shown below – where data is provided for gauss points on either side of the freeze/thaw line.



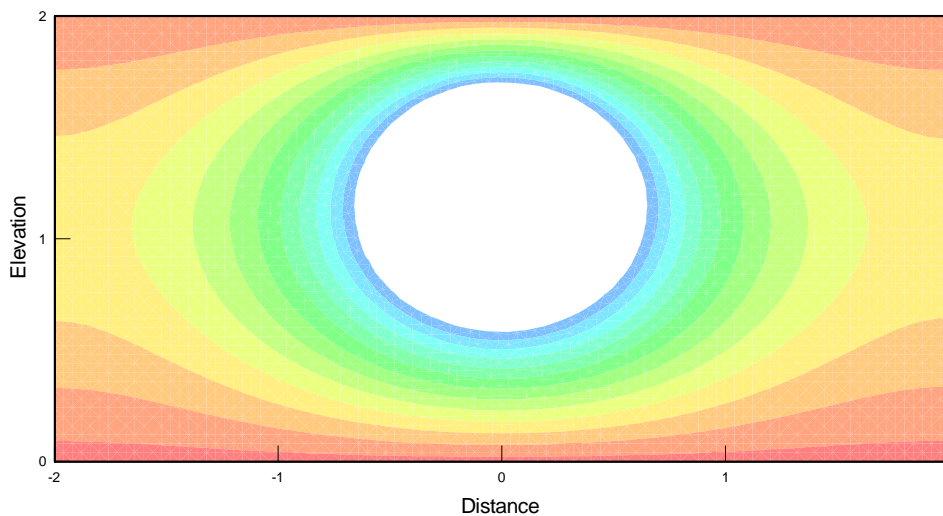
This clearly shows the unfrozen thermal conductivity increasing from about 130 to 250 as the water freezes; while the heat capacity drops from 2900 to 1450.

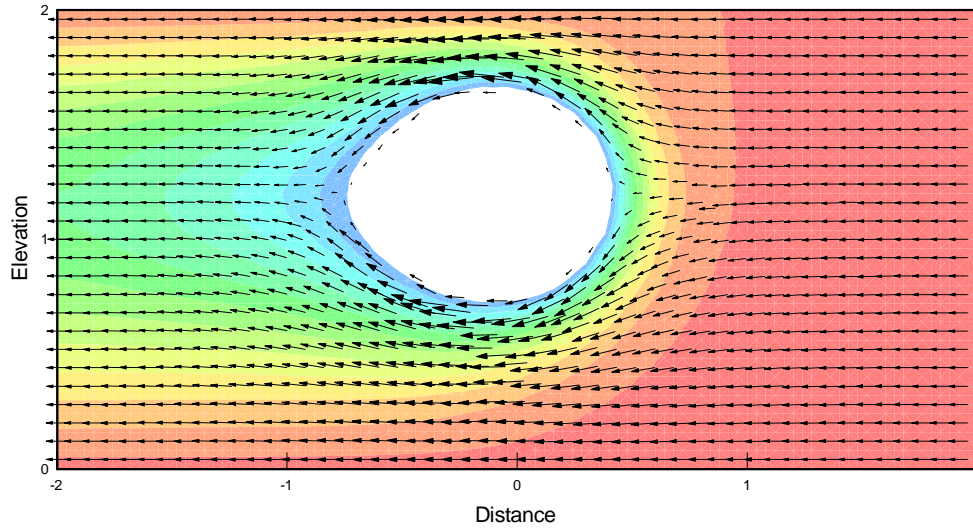
5 Discussion

It is important to verify that the steady state seepage condition is providing the appropriate velocities. The image below is a Gauss Region result from the seepage steady state file. You can see that the velocity is 0.71 m/day and the gradient is 0.005, which is what our intent was when we set up the boundary conditions. The values are not exact, because there is a hole in the mesh that is altering the flow regime slightly.



The following two images shows the temperature contours around the frozen zones for the conduction only case and the coupled convective case. There are no water flow vectors in the conduction only image. However, in the second image with water flow, you can see how the water must flow around the growing frozen zone.





The next image is a graph on a cut line that shows how the velocity in the x direction is increasing due to the constricted cross sectional area for flow between the growing frozen zone and the bottom of the model domain. If the velocity increases too much, then the frozen growth will stop. In other words, the same amount of heat is being added by the flowing water as is being removed by the cold pipe, and no more frozen zone expansion can occur. This has very severe consequences in cases such as artificial ground freezing, when frozen zones around adjacent freeze pipes cannot grow together because of increasing water velocity in the unfrozen gap.

