SVHEAT™

2D / 3D Geothermal Modeling Software

Verification Manual

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1 INTRODUCTION

The word “Verification”, when used in connection with computer software can be defined as “the ability of the computer code to provide a solution consistent with the physics defined by the governing partial differential equation, PDE”. There are also other factors such as initial conditions, boundary conditions, and control variables that also affect the accuracy of the code to perform as stated.

“Verification” is generally achieved by solving a series of so-called “benchmark” problems. “Benchmark” problems are problems for which there is a closed-form solution or for which the solution has become “reasonably certain” as a result of long-hand calculations that have been performed. Publication of the “benchmark” solutions in research journals or textbooks also lends credibility to the solution. There are also example problems that have been solved and published in User Manual documentation associated with other comparable software packages. While these are valuables checks to perform, it must be realized that it is possible that errors can be transferred from one’s software solution to another. Consequently, care must be taken in performing the “verification” process on a particular software package. It must also be remembered there is never such a thing as complete software verification for “all” possible problems. Rather, it is an ongoing process that establishes credibility with time.

SoilVision Systems takes the process of “verification” most seriously and has undertaken a wide range of steps to ensure that the SVHEAT software will perform as intended by the theory of saturated-unsaturated freezing and thawing.

The following models represent comparisons made to textbook solutions, hand calculations, and other software packages. We at SoilVision Systems Ltd. are dedicated to providing our clients with reliable and tested software. While the following list of example models is comprehensive, it does not reflect the entirety of models, which may be posed to the SVHEAT software. It is our recommendation that water balance checking be performed on all model runs prior to presentation of results. It is also our recommendation that the modeling process move from simple to complex models with simpler models being verified through the use of hand calculations or simple spreadsheet calculations.

2 TWO-DIMENSIONAL HEAT TRANSFER

This Chapter will verify the ability of SVHEAT to solve two dimensional steady-state and transient heat transfer models. The results from SVHEAT are compared to published analytical results as well as other proven commercial software packages. Each verification model will begin with a brief description of the model followed by the comparison of results and finally conclusions about the model. All of the verification models presented in this document are included with the SVHEAT software under the VerifySVHEAT project.

2.1 HARLAN AND NIXON

Harlan and Nixon solves for the steady-state conditions between two adjacent areas with surface temperatures of +4°C and -5°C. The results from SVHEAT will be compared to the results of an analytical solution published by Harlan and Nixon (1978).

Project:	GeoThermal
Model:	Verification01

2.1.1 Model Description

In order to simulate the conditions proposed in Harlan and Nixon it was necessary to set the thermal conductivity to 1.0 J/s-m-C for the range of temperatures expected in the model. This is accomplished by entering at least two points on the thermal conductivity curve giving both points a thermal conductivity of 1.0.

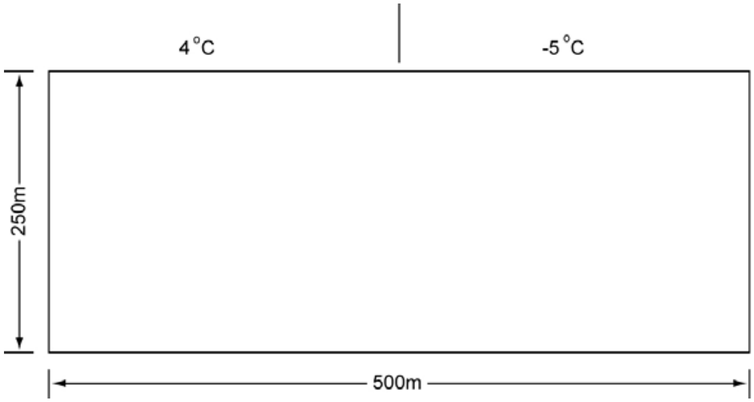

Figure 1 Verification #1 Model Description

The model is setup to model two adjacent semi infinite areas. One area with a surface temperature of +4°C the other with a surface temperature of -5°C. SVHEAT will solve for the resulting ground temperatures resulting from the applied boundary conditions.

2.1.2 Results and Discussion

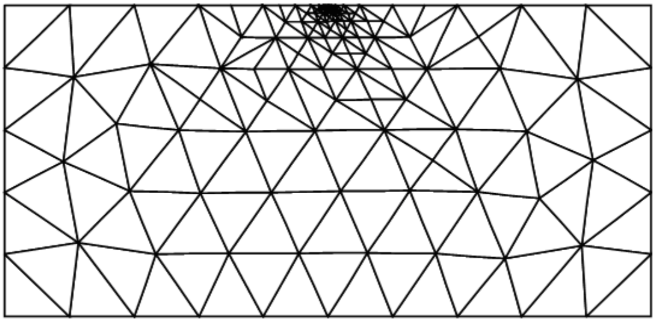

Figure 2 SVHEAT Solution Mesh

The ability of SVHEAT to provide automatic mesh generation and refinement simplifies the modeling process. This feature automatically creates a mesh within the boundaries of the model domain. The solution mesh for the model at hand may be seen in Figure 2.

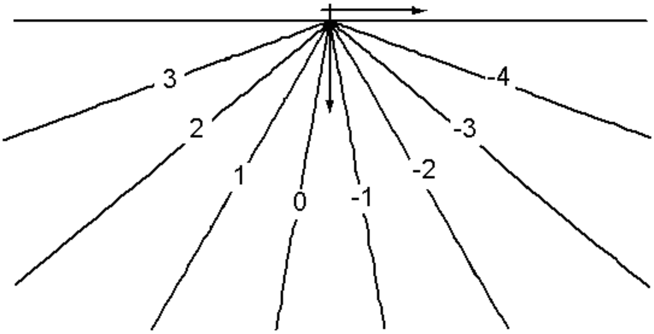

Figure 3 SVHEAT Temperature Contours

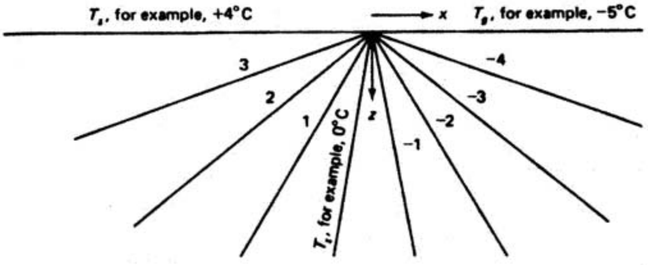

Figure 4 Analytical Results (Harlan and Nixon 1978)

Comparing the above contour plots of temperature SVHEAT and the analytical solution published in Harlan and Nixon one can see that there is good agreement. Both solutions show agreement in the location of the freezing front as well as the remaining temperature contours in both the frozen and thawed material.

2.2 HEATED STRIP

The second verification model will be used as a forum to compare SVHEAT to the TEMP/W software package. The steady-state model will consider a heated strip extending across permafrost conditions.

Project: GeoThermal
Model: HeatedStrip

2.2.1 Model Description

The presented example illustrates the effect of a warm building on the subsurface during sub-zero conditions outside.

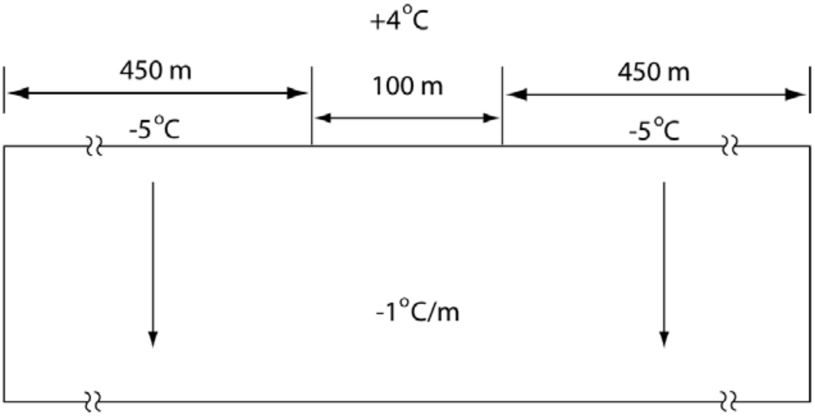

Figure 5 Model Description and Geometry

This model is designed to simulate a heated strip extending across permafrost conditions. The initial surface temperature is -5°C and increases with depth at a rate of 1°C/30m. The heated strip remains at a constant temperature of +4°C. Due to the symmetry that exists, only half of the model will be considered.

2.2.2 Results and Discussion

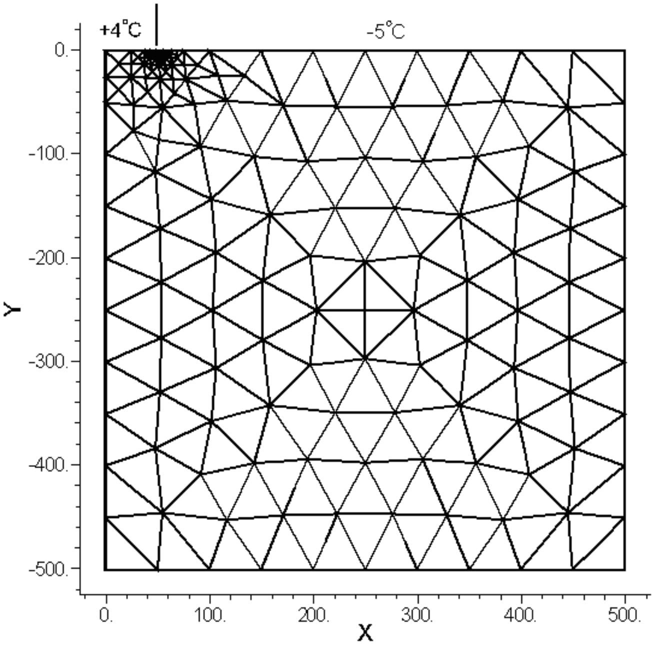

Figure 6 Heated Strip SVHEAT Solution Mesh (Error=0.01°C)

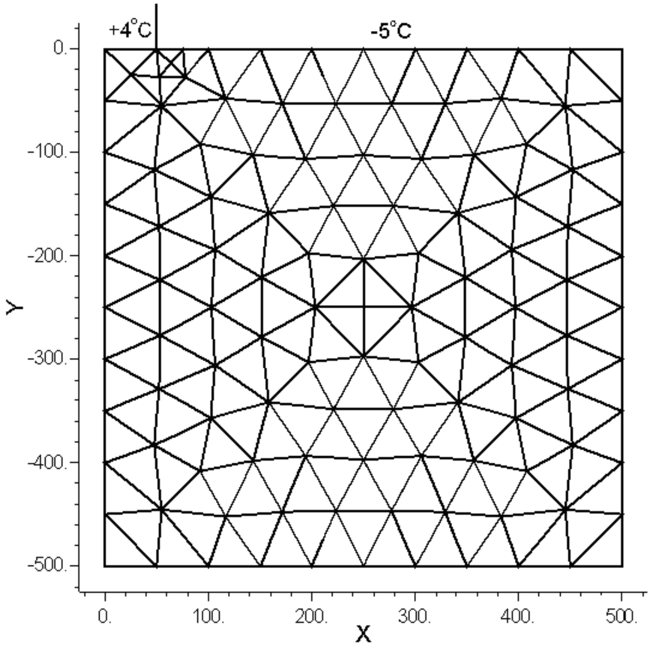

Figure 7 Heated Strip SVHEAT Solution Mesh (Error=0.015°C)

A refined mesh is necessary around areas where errors are expected to be high to ensure convergence and solution accuracy. How much resolution is required to achieve the proper balance between solution accuracy and efficiency? If the mesh has too much resolution the modeler sacrifices efficiency while not enough resolution will sacrifice solution accuracy. In fixed mesh software, it is left up to the user to determine where in the model this error is most likely to occur.

SVHEAT allows the user to set the error for each model by entering a global error limit, which is to be achieved. The mesh is subsequently refine until this error limit is achieved. The three figures above illustrate how the solution mesh will change depending on the error limit set in the model SVHEAT can generate meshes that would be impossible to create by hand and therefore provides an increased level of accuracy and convergence ability.

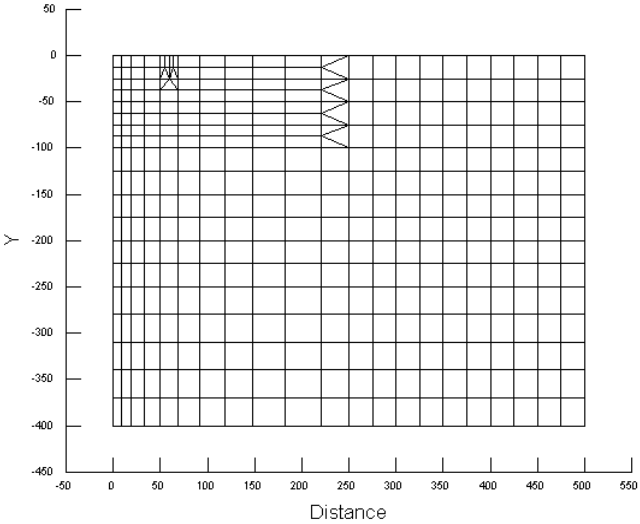

Figure 8 Verification #2 TEMP/W Solution Mesh

An experienced engineer understands that a refined mesh is necessary around areas where errors are expected to be high to ensure convergence and solution accuracy. However, even the most experienced engineers may question how much resolution to include to achieved the balance between solution accuracy and efficiency they are looking for.

If the mesh has too much resolution the modeler sacrifices efficiency while not enough resolution will sacrifice solution accuracy. Most software packages today do not supply the user with a way to quantify how much error they are allowing in their solution. In addition, it is left up to the user to determine where in the model this error is most likely to occur. SVHEAT allows the user to set the error for each model by typing in a single number and automatically refines the mesh in model areas resulting in significant time-savings.

A comparison between error limits can be generated as easily as saving the model under a new name using *Save As*, setting a new error limit, and running the model to see the results. The three figures above illustrate how the solution mesh will change depending on the error limit set in the model. SVHEAT can generate meshes that would be impossible to create by hand and therefore provides a level of accuracy and convergence ability that far surpasses current software.

The results in the subsequent figures show good agreement between the two software packages. The two figures also illustrate how easy it is to determine solution accuracy using SVHEAT.

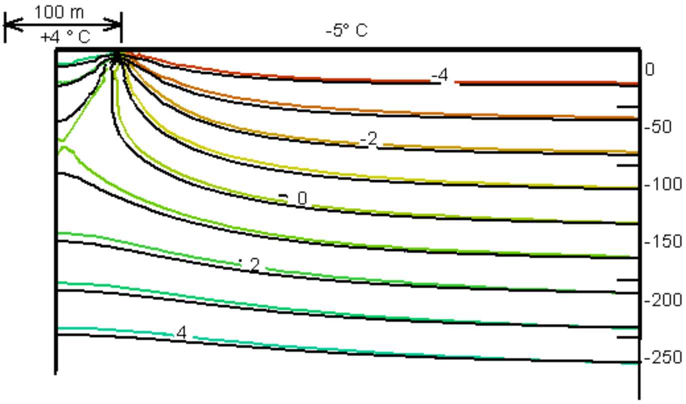

Figure 9 SVHEAT color (printed light) versus TEMP/W (Error=.015 °C)

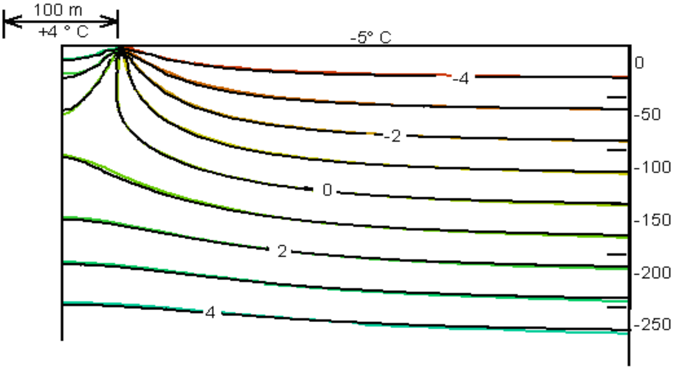

Figure 10 SVHEAT color (printed light) versus TEMP/W (Error=.01)

2.3 COUTTES AND KONRAD (1994)

The third verification model was originally published by Couttes and Konrad (1994) to look at the case of chilled pipelines stretching across areas of discontinuous permafrost. TEMP/W uses this model as verification therefore the results obtained from SVHEAT will be compared to those found in the TEMP/W User's Manual.

Project:	GeoThermal
Model:	T_CouttesKonrad

2.3.1 Model Description

The material properties that were used in the model are presented below:

Table 1 Thermal Conductivity and Unfrozen Water Content soil property curves

Temperature	Conductivity
-10	1.56E+05
-1	1.56E+05
-0.1	1.56E+05
0	1.43E+05
0.1	1.30E+05
1	1.30E+05
10	1.30E+05

Temperature	Unfrozen W.C.
-10	0
-1	0.001
-0.1	0.002
-0.05	0.25
0	0.5
0.05	0.75
0.1	0.998
1	0.999
10	1

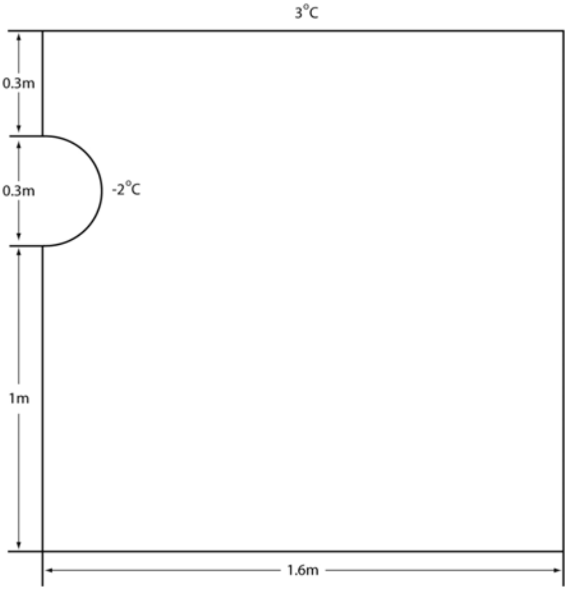

Figure 11 2D Pipe Geometry and Boundary Conditions

A chilled pipeline with an outside temperature of -2 C is buried in material with an initial temperature of 3 C. The results will show the condition of the material after a time period of 730 days. The ground surface temperature is kept constant at 3 C.

2.3.2 Results and Discussion

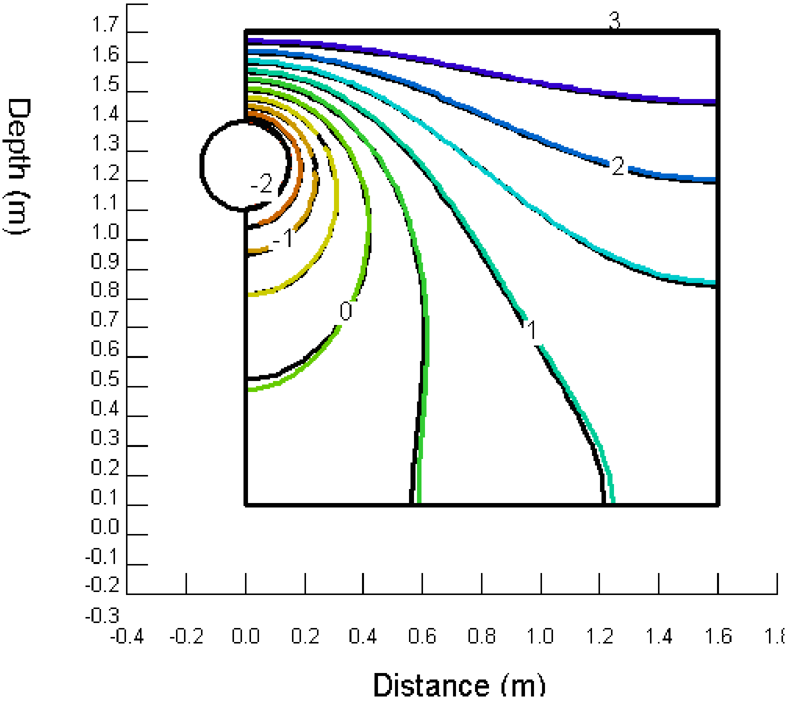

Figure 12 SVHEAT (color or light) versus TEMP/W (black) 730 days

From the above figure it can be seen that there is good agreement between the two software packages on the location of the freezing front as well as the condition of the material in both the frozen and unfrozen areas.

2.4 1D HORIZONAL SOIL COLUMN (JAME, 1977)

Jame (1977) conducted a serial of 1D soil column freezing experiments. His experimental data has been used in verification of many numerical calculations (Jame, 1977, Taylor and Luthin, 1978, and Newman, 1995).

Project: Hydro-Heat Coupling
Model: Jame -1D Horizontal Soil Column

2.4.1 Model Description

Model geometry:
Soil column length: 30 cm

Material Properties
Soil name: Silica flour,

Soil hydraulic properties of SVFlux:
Saturated volumetric water content = 0.49,
Hydraulic conductivity: 0.01079 m/hr,
SWCC fitting equation: Fredlund and Xing

The data used in SWCC fitting is from the experimental data of unfrozen water content as function of negative temperature (Jame 1977). The matric suction is converted from the temperature based on Clapeyron equation. Figure 13 is the SWCC fitting used in this model with parameters of af = 127.7809 kPa, nf = 1.281422, mf = 2.002947, and hr = 673.7741 kPa.

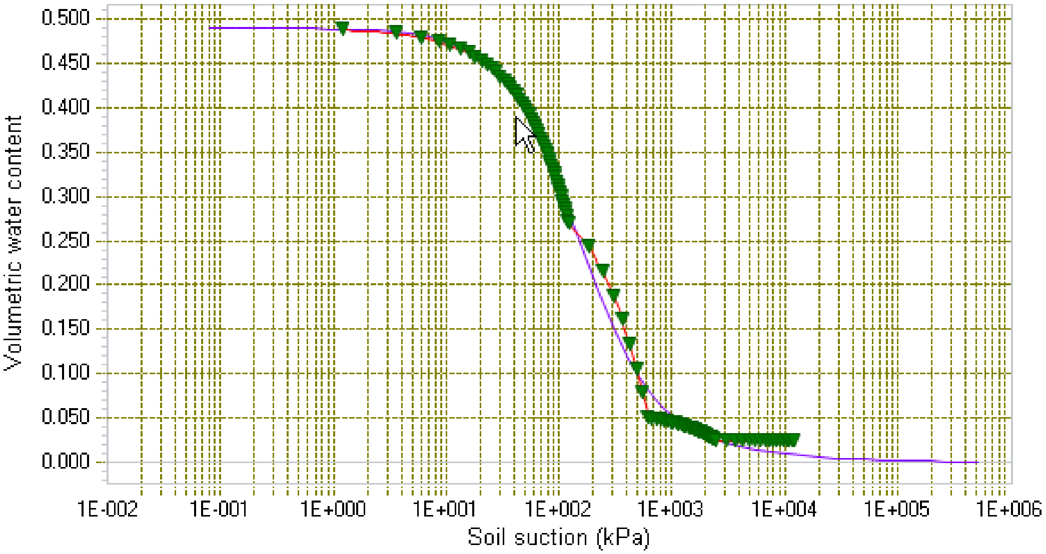

Figure 13. Soil water characteristic curve (SWCC)

Soil thermal properties of SVHeat

Thermal conductivity is calculated based on formulation obtained by Johansen (1975).

Thermal conductivity of soil solid component: 8.25 J/s-m-C
Soil dry density: 1330 kg/m^3

Soil heat capacity is calculated based on

$$C = \gamma_d [c_s + 4180 w_u + 2100 w_i] \quad [1]$$

where:

C = volumetric specific heat capacity, $J/m^3 °C$

γ_d = dry density of soil, 1330 kg/m^3

c_s = specific heat capacity of soil particles, 837 $J/kg°C$

w_u = unfrozen water content expressed in % of weight of the soil

w_i = ice content in % of dry weight of the soil

Soil freezing characteristic curve (SFCC)

SFCC is represented with the same SWCC as shown in Figure 13, and Clapeyron equation is used to convert temperature into matric suction in calculation of unfrozen water content and hydraulic below soil freezing point.

Boundary condition
One end of soil column is applied to cold temperature with freezing rate given below.

$$\begin{aligned} Te &= -7.6 * t \quad \text{if } t < 0.5 \\ Te &= -3.8 - 2.4/3.5 * (t - 0.5) \quad \text{if } t < 4 \\ Te &= -5.9 \quad \text{if } t >= 4 \end{aligned} \qquad \textbf{[2]}$$

where

t = time, hr

Te = cold end temperature of soil column, $°C$

The other end of soil column is keeping warm temperature of 4.2 $°C$

No water flows in or out from both ends of soil column.

Initial conditions
Temperature = 4.5 $°C$
Pore water pressure = -250 KPa

2.4.2 Results and discussion

The model is setting to run 180 hours, but at about 80 hours, steady state is reached. The result is shown in figure 14. The calculation with the model has a very good agreement with the experimental data.

During the simulation, it was found that it is important to determine soil water phase starting temperature and phase end temperature. In this simulation, the phase starting and end temperature is estimated by SWCC parameter of af and hr based on Clapeyron equation.

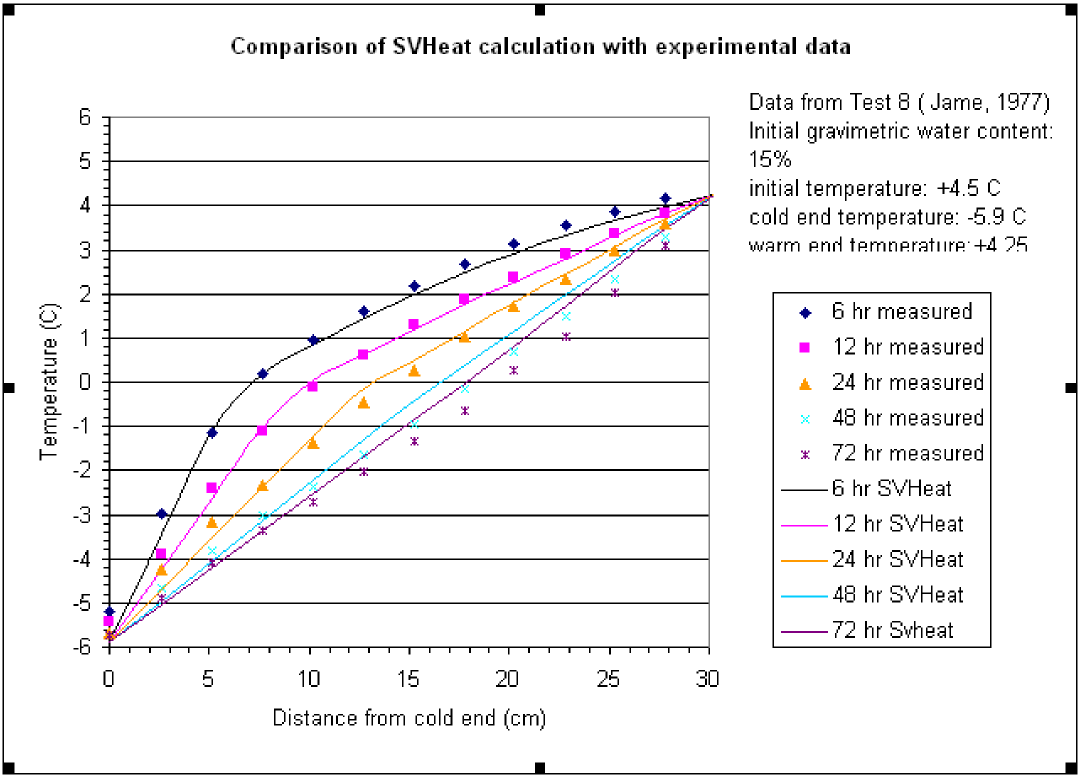

Figure 14. Comparison of calculation of SVHeat/SVFlux model with experimental data

3 REFERENCES

Couttes, R.J. and J.-M. Konrad, (1994). Finite element modeling of transient non-linear heat flow using the node state method. Ground Freezing 94. Balkema, Rotterdam, Netherlands, pp. 39-47.

Harlan, R.L. and J.F. Nixon, (1978). Ground Thermal Regime. In Geotechnical Engineering for Cold Regions, eds. Andersland, O.B. and Anderson, D.M. pp. 103-163.

TEMP/W User's Guide, (1991-2001). GEO-SLOPE International Ltd., Calgary, Alberta, Canada

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