GeoStudio Example File
Heat Pulse Technique

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Introduction

The general mechanisms through which heat is transferred in soils are conduction, convection, and phase change. Heat conduction occurs as hot moving atoms, molecules, and electrons collide, and transfer energy whereas heat convection occurs as pore fluid moves within the soil. The fluid movement can either be generated by buoyancy forces (natural convection) or by external forces, such as pressure (forced convection or advection). Phase change, on the other hand, is associated with the characteristic amount of energy released or absorbed by a fluid as it transitions from one state to another. The key thermal properties needed to account for these mechanisms are thermal conductivity, volumetric heat capacity, and latent heat. Both thermal conductivity and volumetric heat capacity can be estimated from measurements of the thermal field around a heating element. The sensors used for this purpose generally consist of small parallel cylindrical probes, which either contain a heating element or a thermistor (Campbell et al., 1991; Bristow et al., 1994). Further developments of this technique, referred to as the heat pulse technique, have led to the simultaneous estimation of both soil thermal properties and soil water flux (Ren et al., 2000; Mortensen et al., 2006; Hopmans et al., 2002).

The objective of this example is to verify the forced convection (or advection) formulation against an analytical solution of the heat pulse problem with and without groundwater flow. The verification exercise lends credibility to the use of the formulation for problems involving forced convection in porous media.

Background

The heat pulse sensor generally consists of three probes lying in a common plane, which is aligned parallel to the direction of groundwater flow. As shown in Figure 1, the central probe acts as a heat emitter while the outer probes measure the upstream and downstream changes in temperature through time. To ensure rapid temperature measurements, the probes are designed with small heat capacity and large thermal conductivity. Although the heating element is a point in space, it expands into an infinite line source in a two-dimensional analysis. In other words, the point extends into the page. The analytical solution to the heat equation for an infinite line source in an infinite moving medium reads as follows (Ren et al., 2000):

$$\Theta_u = \frac{T_u(t) - T_o}{Q_{t,\,source}/(4\pi k_t)} = \begin{cases} \displaystyle\int_{s=0}^{t} s^{-1} exp\left[-\frac{(y_u + vs)^2}{4\frac{k_t}{C_t}s}\right] ds & 0 < t \le t_o \\ \displaystyle\int_{s=t-t_o}^{t} s^{-1} exp\left[-\frac{(y_u + vs)^2}{4\frac{k_t}{C_t}s}\right] ds & t > t_o \end{cases}$$

Equation 1

$$\Theta_d = \frac{T_d(t) - T_o}{Q_{t,\,source}/(4\pi k_t)} = \begin{cases} \displaystyle\int_{s=0}^{t} s^{-1} exp\left[-\frac{(y_d - vs)^2}{4\frac{k_t}{C_t}s}\right] ds & 0 < t \le t_o \\ \displaystyle\int_{s=t-t_o}^{t} s^{-1} exp\left[-\frac{(y_d - vs)^2}{4\frac{k_t}{C_t}s}\right] ds & t > t_o \end{cases} \qquad \text{Equation 2}$$

where Θ is the dimensionless temperature, T_o is the initial temperature, $Q_{t,source}$ is the heat source per unit length, k_t is the thermal conductivity of the soil, s is the variable of integration, y is the direction parallel to the groundwater flow with an origin at the heating element, $v = q_w \frac{C_{t,w}}{C_t}$ is the thermal front advection velocity (or heat pulse velocity), q_w is the volumetric flux of water, $C_{t,w}$ is the volumetric heat capacity of water, C_t is the volumetric heat capacity of the soil, and t_o is the duration of the heat pulse. Subscripts *u* and *d* refer to upstream and downstream positions, respectively.

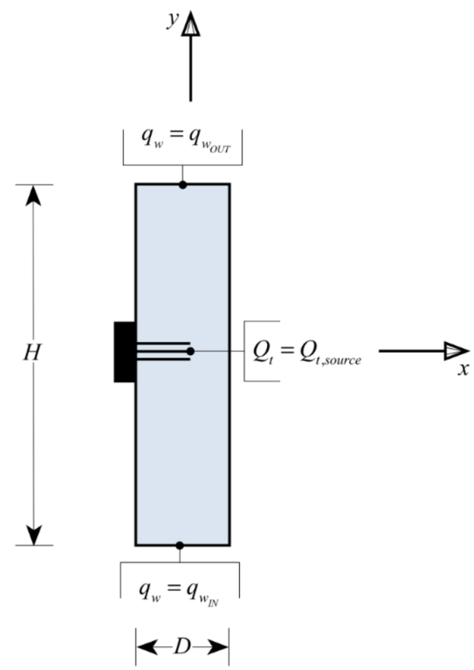

Figure 1. Schematic representation of the laboratory experiment with boundary conditions.

Numerical Simulation

The ability of the model is evaluated with typical laboratory experiments in which heat pulse sensors, with 6 mm-spaced probes, are inserted into a 69 mm-diameter and 270 mm-tall cylindrical soil column packed with saturated Hanlon sand. The evenly spaced probes are 40 mmlong and 1.3 mm in diameter. The heat pulse duration is 15 s and its strength is 50 J/s/m. The experiments are conducted at a constant room temperature of 20°C, and the volumetric heat capacity of the water is equal to 4.186×10^{6} J/m^{3}/°C. The thermal conductivity and volumetric heat capacity of the saturated Hanlon sand sample is equal to 1.95 J/s/m/°C and 3.07×10^{6} J/m^{3}/°C, respectively. The applied groundwater fluxes range from 0 to 6.31×10^{-5} m/s.

Results and Discussion

Figure 2 shows the results of the heat pulse experiment without groundwater flow. In this particular case, the thermal process is governed by conduction, and the temperature response at the upstream and downstream probes are identical. As expected, the temperature rapidly increases, reaches a maximum, and then slowly decreases with time. The time-lag between the heat pulse and its manifestation at the outer probes is ascribed to the soil thermal properties and the distance between the inner and outer probes. As expected, the results are in very close agreement with the analytical solution.

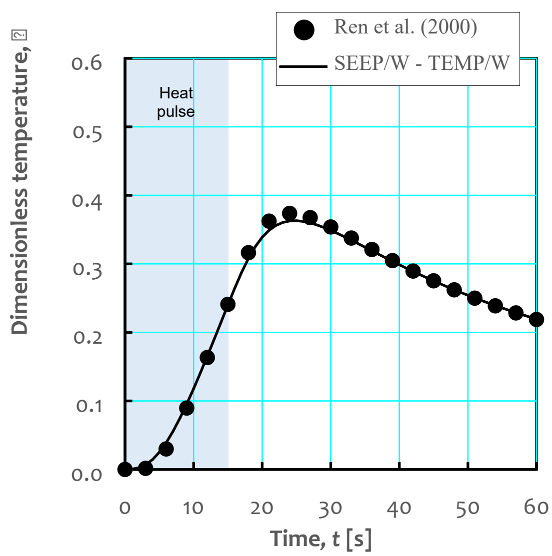

Figure 2. Dimensionless temperature response at the upstream and downstream probes without forced convection.

Figure 3 shows the results of the heat pulse experiments with groundwater flow. As anticipated, the groundwater flow results in greater temperature rise at the downstream probe and smaller temperature rise at the upstream probe. These changes in amplitude are caused by the different travel times of the heat pulse. The difference between the upstream and downstream temperatures increases with increasing superficial flux. Once again, the results are in very close agreement with the analytical solution.

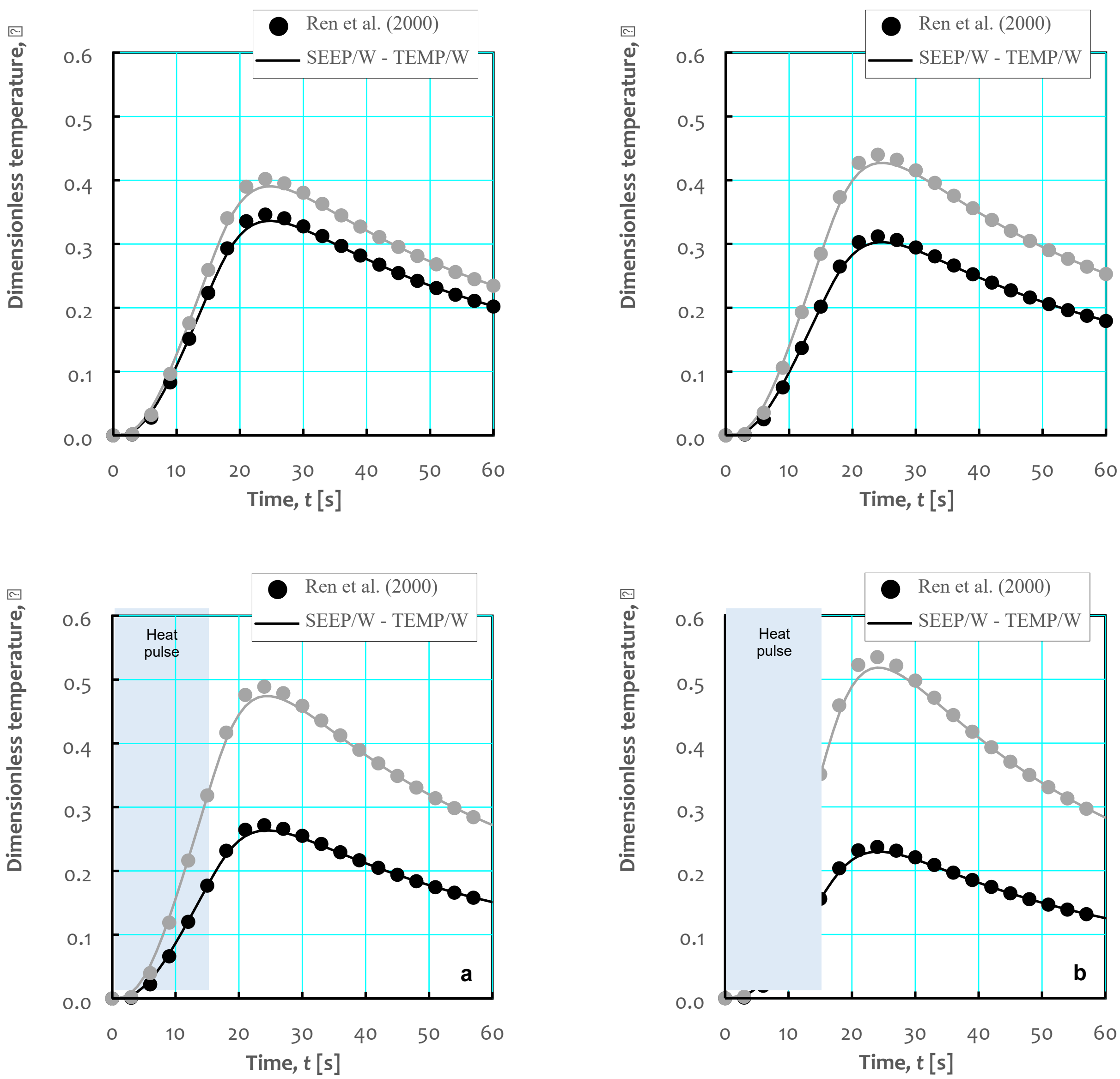

Figure 3. Dimensionless temperature response at the upstream and downstream probes with forced on. (a) $q_w = 1.16\times10^{-5}$ m/s. (b) $q_w = 2.67\times10^{-5}$ m/s. (c) 5×10^{-5} m/s. (d) $q_w = 6.31\times10^{-5}$ m/s.

Heat pulse

Heat pulse

Summ and Conclusions

The obje this example was to demonstrate the ability forced convection problems with SEE EMP/W. The capabilities of the model were ed with an analytical solution for the he e problem with and without groundwater flo undwater flow was shown to influence t pulse travel time, and result in different the sponses at the upstream and downstre bes. The results were generally shown to be close agreement with those of the ana solution.

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References

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