INCORPORATION OF GROUNDWATER FLOW INTO NUMERICAL MODELS AND DESIGN MODELS

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KEY WORDS

computer simulation, ground-coupled, ground-source heat pumps, groundwater, heat pump, heat exchanger, heat transfer, numerical models.

PROJECT BACKGROUND AND STATUS

This project originated in May 1998 out of the recognition that convective transport of heat by moving groundwater may be an important factor in reducing the necessary size of closed-loop ground-coupled heat exchangers. Green and Perry (1961) demonstrated that the value of effective thermal conductivity is greater with a flowing fluid than with a stagnant fluid and, in general, effective thermal conductivity increases with increasing fluid flow rate. Current design and simulation models for closed-loop systems assume that heat transfer within geologic formations occurs by conduction only.

In the absence of previous studies in this field, there is therefore a need to make a preliminary investigation, firstly of the beneficial effects of groundwater flow on system costs, and secondly, the ability of current design methods to adequately deal with conditions of significant groundwater flow. The potential reductions in first cost where there is significant groundwater flow may be large. Although the availability of aquifers varies, there are many densely populated areas of the U.S., e.g. the East coast, where aquifers are prevalent.

The original lifetime of this project was approximately two years. However, the project was terminated at the end of 1998. Accordingly work completed up to December 1998 is reported here.

PROJECT OBJECTIVES

The overall objectives of this project are to make a preliminary investigation of the effects of groundwater flow on the design and performance of vertical closed-loop ground heat exchangers. Based on the investigation results, the need for development of groundwater flow models that can be used within existing design tools will be evaluated.

Technical Objectives

- Model the effects of groundwater flow on the heat transfer from a single U-tube ground heat exchanger under a range of hydrological conditions.
- Assess the impact of groundwater flow on the analysis of data collected from in-situ ground thermal conductivity tests.
- Assess the validity of current system design models in situations where groundwater flow is significant.

Expected Outcomes

- Better advice will be available for designers and contractors who work in regions with significant groundwater flow.
- Significant reductions in ground-loop heat exchanger lengths may be seen in cases where heat advection by groundwater flow is high. In some of the cases examined in this work the reduction amounted to more than 25%.

APPROACH

The first task of this project was to select a numerical groundwater flow and heat transport model. Numerous commercially available and public domain software codes were reviewed with particular attention being given to (a) the suitability of the discretization and solution methods, (b) allowable boundary conditions, (c) ease of data handling, and (d) cost. The code finally selected was one that simulates transient three-dimensional groundwater flow with solute or heat transport using the Galerkin finite element method and which can deal with complex transient boundary condition data.

Prior to performing the computer simulations, typical hydraulic and thermal properties of soils and rocks were compiled from the literature. These data were used as subsequent input to the numerical groundwater flow and heat transport model. Hydraulic property values were taken from Domenico and Schwartz (1990) and thermal property values were taken from Hellstrom (1991).

The computer modeling consisted of a number of single borehole and multi-borehole field simulations. First, the model was used to simulate and observe the effects of groundwater flow on the average fluid temperature in a single U-tube borehole in various geologic materials. Second, the model was used to simulate several in-situ ground thermal conductivity tests with varying groundwater flow velocities. The material selected for these simulations was a coarse sand soil, based on the results of the first set of simulations. For each test case, the model results, along with the thermal loads from an actual building, were used to design a hypothetical multi-borehole field by employing conventional design tools and procedures (i.e. conduction-based models). Finally, the model was used to simulate the long-term performance of each borehole field design. From the results of these simulations, the impact of groundwater flow on the conventional design process was assessed.

RESEARCH RESULTS

For the first set of simulations, the finite element groundwater flow and heat transport model was used to simulate a constant heat flux of 8530 Btu/hr (2500 W) on a U-tube in a 250 ft (76.2 m) deep borehole in various geologic materials. The model was run to two years with a time step of 5 days. Results from two example simulations are shown in Figure 1. Based on these results, and on a Peclet number analysis, it appears that heat convection by groundwater flow is a significant process contributing to heat transfer in coarse-grained soils (sands and gravels) and in rocks exhibiting secondary porosities such fractures and solution channels.

Figure 1 shows that groundwater flow can significantly impact the average borehole fluid temperature. After a one-year period, the average fluid temperature in the borehole where groundwater flow was simulated in the coarse sand is approximately 15 ^{o}F (8.3 ^{o}C) lower than the average fluid temperature in the borehole where no groundwater flow was simulated. Further, the average fluid temperature in the borehole where groundwater flow was simulated reaches steady state conditions almost instantaneously relative to the average fluid temperature in the borehole where no flow was simulated.

For the second set of simulations, the finite element groundwater flow and heat transport model was used to simulate several in-situ ground thermal conductivity tests in a coarse sand soil with varying groundwater flow velocities. In these simulations a constant heat flux was applied for simulation times of 50 hours and 1 week, corresponding to typical durations of in-situ ground thermal conductivity tests.

From the 12 sets of temperature vs. time data generated the effective thermal conductivity was estimated using the method reported by Austin *et al.* (2000). Next, the effective formation thermal was used along with thermal loads from an actual building to determine the design depth of boreholes in a 4 by 4 configuration. Ground-loop heat exchanger design software developed by Spitler et al. (1996) was used for this purpose.

Results of the hypothetical designs are listed for each case in Table 1. A review of these results shows that as groundwater flow velocity increases, the predicted effective thermal conductivity values are significantly different, depending on the time length of the data set (i.e. 50 hours or 1 week). These values are "effective" values since they include the effects of groundwater advection; they are obviously not representative of true thermal conductivity values of the formation. However, at this stage of the design process, it is not clear if the 50-hour data set or the 1-week data set produces more representative values, or if either data set produces representative values at all.

Finally, for the third set of simulations, the finite element model was used to simulate the performance of each borehole field (designed using the simulated in-situ ground thermal conductivity test results) over a ten year period. The simulated heat flux at the internal boundary nodes defining the U-tube pipes corresponded to the monthly heat loads for the test building. Hydraulic and thermal properties for each case listed in Table 1.

Annual maximum and minimum peak temperatures are plotted for each case in Figure 2. Since the test building is cooling-dominated, only peak maximum temperatures are shown. A review of these plots shows that conduction-based models do not adequately predict effective thermal conductivity from in-situ test data in cases where groundwater flow is significant. Based on these results, as groundwater flow velocity increases, the predicted formation thermal conductivity becomes much more sensitive to the duration of the in-situ test. This is shown by cases 5 and 6 and cases 11 and 12. In the remaining cases, the maximum peak temperatures indicate that the systems are over-designed.

From these numerical studies the following conclusions were made:

- Where there is groundwater flow borehole costs may be reduced (by more than 25% in some cases) compared to situations without groundwater flow.
- Current in-situ thermal conductivity measurement methods over predict the thermal conductivity where there is notable groundwater flow.
- Using in-situ measured thermal conductivities in current design procedures may result in over designed borehole fields where there is significant groundwater flow. However, in some circumstances an under designed borehole field may also result.

FUTURE PLANS

This project was terminated as of December 1998 and no future plans exist at this time.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Type and Extent of Interest
Ewbanks and Associates	Effects of aquifer flow on in situ test results.
Geothermal Design and Engineering	Effects of aquifer flow on system design.
Northern Geothermal Support Center	Effects of aquifer flow on in situ test results.

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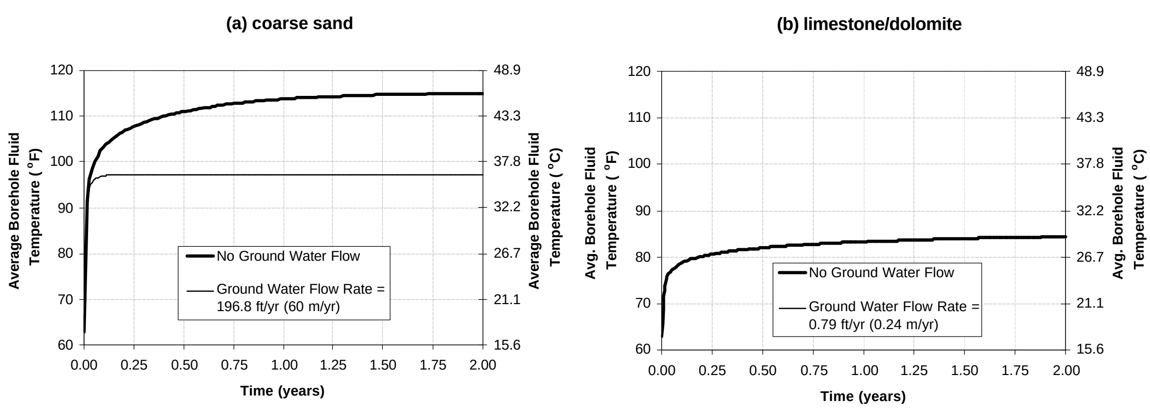

Figure 1. Average borehole fluid temperature vs. time for (a) coarse sand and (b) limestone/dolomite.

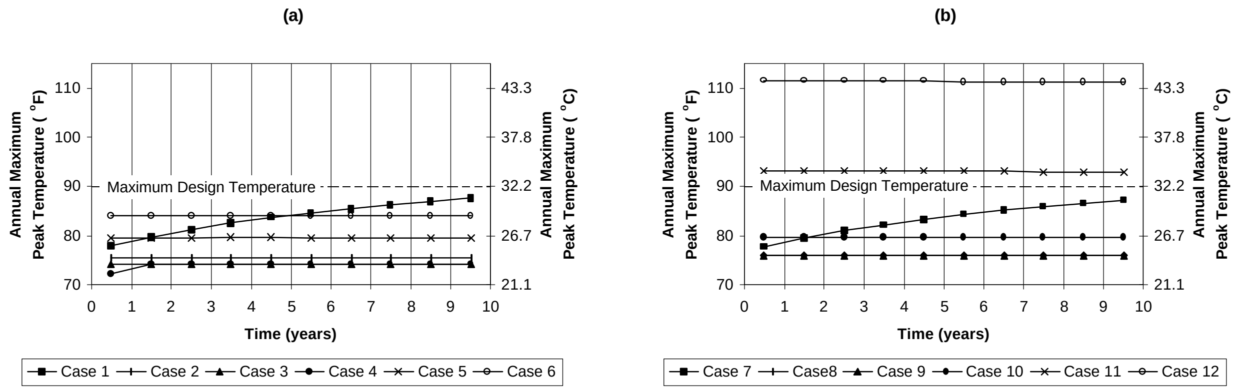

Figure 2. Annual peak maximum average borehole fluid temperatures for the 16 borehole field simulations for simulated in-situ thermal conductivity

TABLE 1
Summary of Borehole Field Design Parameters for Each Test Case

Case Number	Simulation Time (hours)	Ground Water Flow Rate ft/yr (m/yr)	Ground Thermal Conductivity Determined by Numerical Model of Yavuzturk et al. (1999) Btu/hr-ft-^{o}F (W/m-^{o}C)	Design Borehole Depth Predicted by Commercial Design Software ft (m)
1	50	0	0.643 (1.11)	239.98 (73.15)
2	50	196.85 (60.00)	0.650 (1.12)	238.56 (72.71)
3	50	393.70 (120.00)	0.731 (1.26)	224.10 (68.31)
4	50	787.40 (240.00)	1.146 (1.98)	171.56 (52.29)
5	50	1574.80 (480.00)	3.657 (6.33)	87.24 (26.59)
6	50	1968.50 (600.00)	6.074 (10.51)	61.58 (18.77)
7	168	0	0.625 (1.08)	243.86 (74.33)
8	168	196.85 (60.00)	0.691 (1.20)	230.86 (70.37)
9	168	393.70 (120.00)	0.962 (1.66)	191.58 (58.39)
10	168	787.40 (240.00)	2.250 (3.89)	115.91 (35.33)
11	168	1574.80 (480.00)	8.229 (14.24)	48.02 (14.64)
12	168	1968.50 (600.00)	15.107 (26.14)	26.90 (8.20)