3D modelling of borehole heat exchangers at hydrogeological conditions typical of the north European lowlands, sensitivity studies from Denmark

Per Rasmussen[1], Anker L. Højberg[1] and Claus Ditlefsen[1]

[1] Geological Survey of Denmark and Greenland (GEUS)

Øster Voldgade 10, 1350 København, Denmark

cdi@geus.dk

Keywords: Shallow geothermal energy, sensitivity studies, numerical modelling.

ABSTRACT

A recently completed Danish development and demonstration project has compiled knowledge, tools and best practices for closed loop boreholes combined with detailed mapping of thermal properties of Danish soils as well as 3D modelling of heat and groundwater flow.

In Denmark the topmost 100-200 m are basically characterized by heterogeneous glacial and interglacial sediments on top of preglacial deposits and it thus comprises of a wide range of rock types with varying hydrogeological and thermal properties.

I order to understand and quantify the effect of the present heterogeneous geology, it was necessary to establish complex and detailed numerical models in which these conditions could be described directly in 3D. The FEFLOW software package was used for the modelling studies.

The 3D model scenarios illustrates the sensitivity of various parameters affecting the performances of BHEs under Danish and similar hydrogeological conditions. The present model sensitivity studies have focused on realistic variations in e.g. thermal conductivities, temperature gradients, and groundwater flow gradients.

The natural variations in thermal conductivity of typical Danish sediments have been found to have significant impact on the possible yearly energy intake for a BHE. Thus the estimated energy extraction for the most unfavourable of the geological scenarios is found to be only about 60 % of the energy extraction for the most favourable conditions.

Inclusion of ground water flow in the energy calculations have been found be of significant importance when estimating the possibly yearly energy extraction. The calculations also show that the groundwater flow besides ensuring higher yearly energy extraction helps maintaining an energy balance in the vicinity of the borehole during long term production when compared to situations with no groundwater flow. The importance of groundwater flow is often neglected in standard programs for calculating energy extraction.

3D energy modelling including groundwater flow is a useful tool for analysing and optimizing the energy extraction under heterogeneous hydrogeological conditions. Since it may not be economically feasible to model conditions at smaller plants with only a few boreholes the present results may instead be used as guideline for initial estimates of expected energy extraction at different conditions.

1. INTRODUCTION

The Danish subsoil contains large geothermal resources that can be utilized for heating or cooling. However, the use of shallow geothermal energy in Denmark is relatively limited and basic knowledge and practical experience has been lacking. A recently completed Danish development and demonstration project has compiled knowledge, tools and best practices for closed loop boreholes combined with detailed mapping of thermal properties of Danish soils as well as 3D modelling of heat and groundwater flow (Ditlefsen et al. 2014a; Højberg and Rasmussen 2014).

Several model studies have been reported on the use of borehole heat exchangers (BHE), including analyses of how various factors affect the heat extraction and influence the temperatures in the subsoil. Most cases have ignored the groundwater flow, however in recent years there has been more focus on this issue. Vandenbohede et al (2011) and Dehkordi and Schincarioil (2014) have both included groundwater flow in sensitivity analyses.

2. SHALLOW GEOTHERMAL ENERGY IN DENMARK

In Denmark the topmost 100-200 m are basically characterized by heterogeneous glacial and interglacial sediments on top of preglacial deposits and it thus comprises a wide range of rock types with varying hydrogeological and thermal properties.

In order to investigate the effect of varying geological conditions combined with groundwater flow in typical formations found in Denmark a 3D modelling study of heat extraction from a BHE has been conducted. The main focus of the investigation has been sensitivity studies of the parameters effecting the extraction of energy and the recuperation of the geothermal reservoir.

3. THE FEEFLOW MODEL-SETUP

I order to understand and quantify the effect of the heterogeneous geology in Denmark, it was necessary to establish more complex and detailed numerical models in which these hydrogeological conditions could be described directly in 3D. The FEFLOW software package was used for the modelling studies. FEFLOW uses a finite element solution technique enabling the modelling of relevant components of heat transport processes like the interaction between a dynamic groundwater system and the borehole heat exchanger (BHE) (Diersch et al. 2011a, b).

The model calculations were carried out as a local simulation of heat transfer around one BHE using FEFLOW'S BHE model for a single loop, Fig. 1.

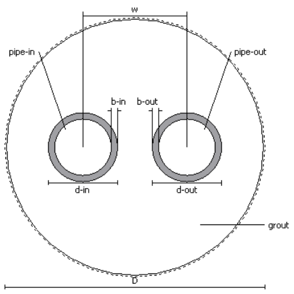

Figure 1: BHE single U-loop (FEFLOW)

In the model setup the BHE was located in the centre of the model domain (Fig. 2). The horizontal extent of the model was 200 m by 200 m and the depth was138 m. The model consisted of 70 horizontal model planes and 69 computational layers of 2 m thickness. Each calculation layer consisted of a triangular net with side lengths ranging from about 0.3 m in the centre of the model to about 15 m at the model's outer boundary. The model calculations were done only for the saturated groundwater. Initial model simulations showed that model boundaries hereby were located far enough from the borehole to avoid unintended effects from model boundaries.

The heat extraction was modelled as alternating operation of the BHE in a one year cycle with a period of constant pumping and heat extraction followed by a period of no pumping for the rest of the one year period.

Groundwater flow was introduced in the model by keeping constant gradients of the groundwater heads for two opposite sides of the model over the whole depth of the model.

The heat transport in the groundwater zone was specified by a constant temperature at the top and at the bottom of the model, as well as a specific temperature gradient at one side of the model.

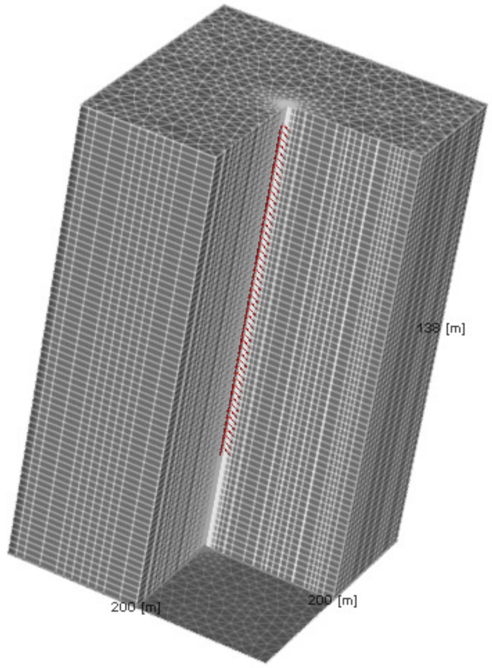

Figure 2: FEFLOW model grid and BHE

I order to follow the changes in temperatures around the BHE during the model simulations 8 observation points (fictive monitoring wells) were placed at different distances from the borehole. One point was located in the centre of the borehole, six observation points in the direction of the groundwater flow from 1 m to 100 m downstream from the borehole, and one point was located perpendicular to the groundwater flow direction 100 m from the borehole (Fig. 3).

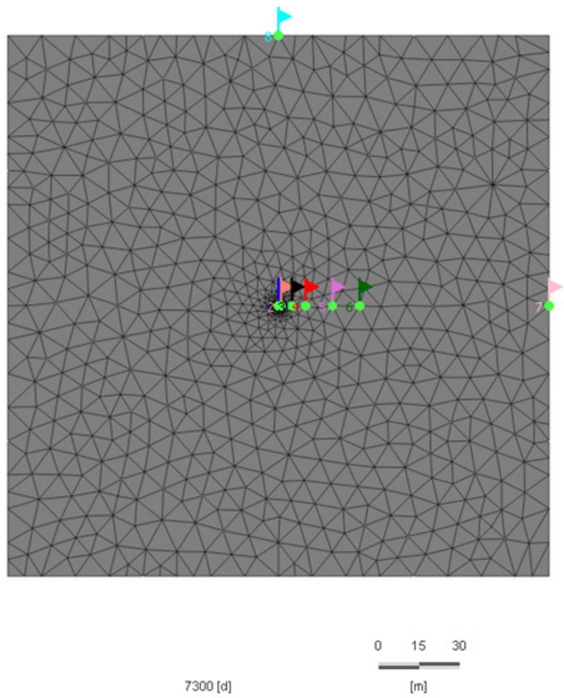

Figure 3: Observation points in the numerical model.

4. SENSITIVITY ANALYSES

Various factors, such as the hydrogeological and geothermal properties of the aquifer and the surrounding aquitards, and the construction and operation of BHEs, will affect the efficiency of the heat extraction. The potentially relevant parameters and their relative importance for the overall heat extraction were investigated by a sensitivity analysis. In the sensitivity analysis the parameters were changed one by one and the effect of the individual parameters were tested through model simulations. By changing the parameters individually, and for each case perform a ten year model calculation of heat extraction or heat storage the importance of each factor was assessed relative to each other and illustrated and compared to a base scenario. The base scenario includes typical groundwater flow and a typical vertical temperature gradient in a sandy aquifer.

4.1 Geology and groundwater flow

As part of the project a mapping of the thermal conductivity of typical shallow Danish sediments was performed (Ditlefsen at al. 2014b) Values from this investigation were used in the sensitivity study. Here it was found that the thermal conductivity of the individual sediment types have great effect on the energy extraction. Thus a difference in the maximum yearly heat abstraction of more than 40 % was found depending on whether the BHE was situated in clayey or sandy sediments. On the other hand the material's specific heat capacity was found to be of little importance. Thus the limiting factor when extraction heat is the thermal conductivity of the surrounding formations and not how much heat the soils can store (Fig. 4).

The presence of ground water flow was found to have a favourable effect on the maximum energy extraction. There was a 13 % higher energy extraction in the situation with a groundwater flow caused by a gradient in the groundwater pressure level of 3 ‰ relative to the absence of a gradient and thus no groundwater flow.

An increased temperature gradient was also shown to result in an increased energy intake. By increasing the temperature gradient in a sand layer sequence from 0 °C to 3 °C / 100 m, the maximum energy absorption was increased by about 15 % (Fig. 5).

During the operation period an ongoing cooling of the surrounding layers resulting in a gradually reduced energy extraction, was observed in the modelling scenarios with no groundwater flow. Thus the calculations showed that the groundwater flow in addition to ensure a higher energy extraction, also helps to maintain the energy balance in the aquifer system in the long run (Fig. 6). The effect of groundwater flow is often neglected in standard programs for calculating energy extraction and thus underestimating the potential energy extraction from layers with a significant flow of groundwater.

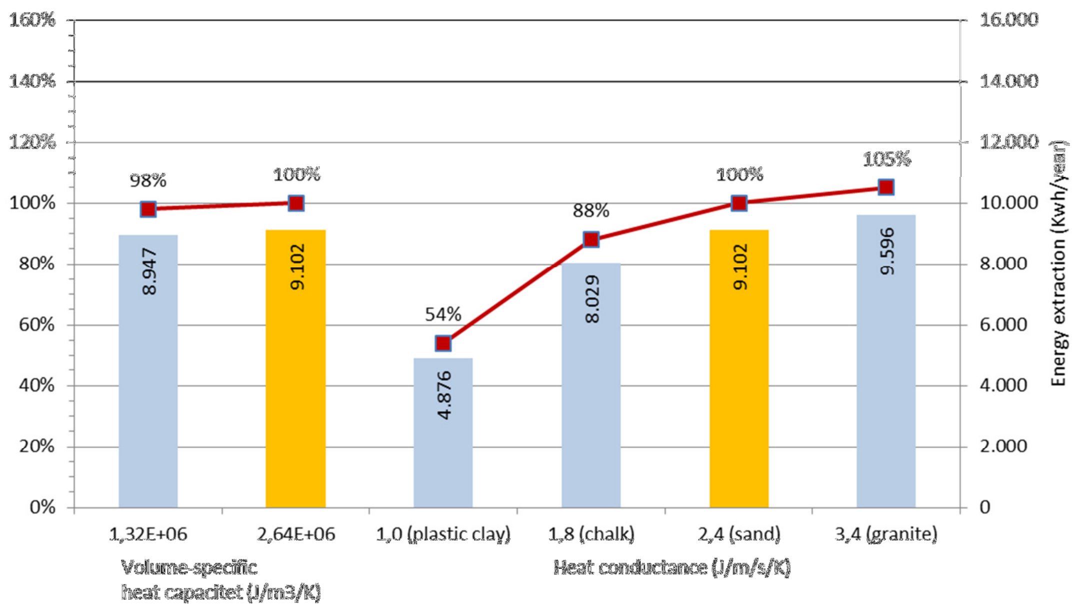

Figure 4: Sensitivity analyses of volume-specific heat capacity and heat conductance with typical values for different soil types. Orange colour bar: the base scenario.

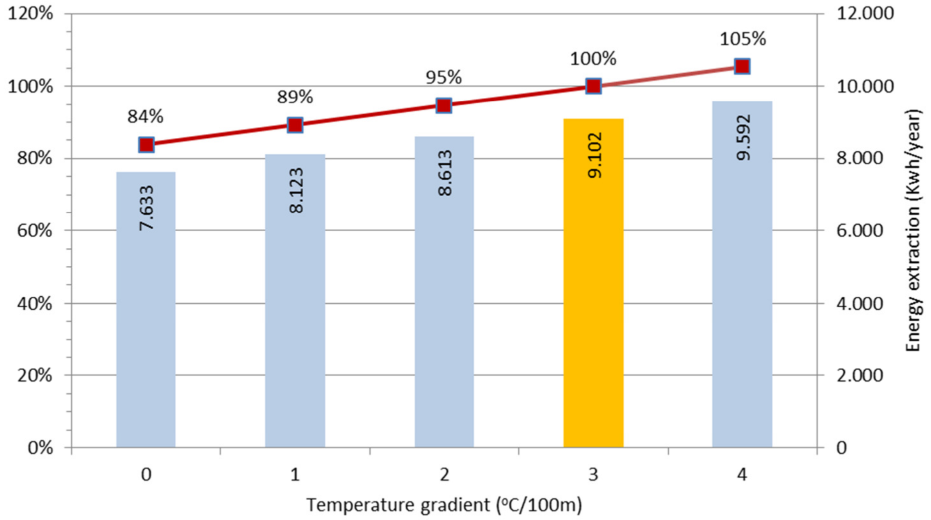

Figure 5: Sensitivity analyses of groundwater temperature gradient. Orange colour bar: the base scenario.

a. **b.**

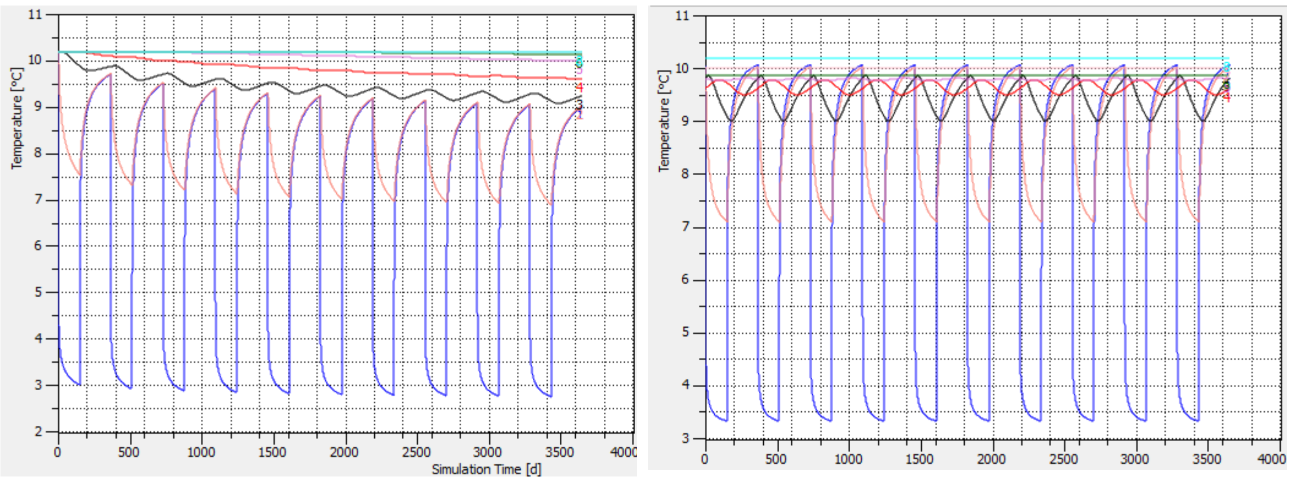

Figure 6: Temperature development during a simulation period of 3650 days (10 years): Figure a: modelling not including groundwater flow. Figure b: modelling including groundwater flow. The different curves represent temperatures in observation points with same colours seen in Fig. 3.

6. CONCLUSIONS

3D numerical energy modelling including groundwater flow is a useful tool for analysing and optimizing the energy extraction under heterogeneous hydrogeological conditions.

In the present study 3D model scenarios illustrates the sensitivity of various parameters affecting the performances of BHEs under Danish and similar hydrogeological conditions. The present model sensitivity studies have focused on realistic variations in e.g. thermal conductivities, temperature gradients, and groundwater flow gradients.

The natural variations in thermal conductivity of typical Danish sediments have been found to have significant impact on the possible yearly energy intake for a BHE. Thus the estimated energy extraction for the most unfavourable of the geological scenarios is found to be only about 60 % of the energy extraction for the most favourable conditions.

Inclusion of ground water flow in the energy calculations have been found to be of significant importance when estimating the possibly yearly energy extraction.

The model calculations also showed that the groundwater flow besides ensuring higher yearly energy extraction also helped maintain an energy balance in the vicinity of the borehole during long term production compared to situations with no groundwater flow. The importance of groundwater flow is often neglected in standard programs for calculating energy extraction.

The numerical model calculations of a typical Danish hydrological setting including groundwater flow indicates that a 3-month annual heating of an aquifer, with an inlet temperature of 35 °C (heat storage) will not have any significant effect on the surrounding environment.

Since it may not be economically feasible to model conditions at smaller plants with only a few boreholes the present results may instead be used as guideline for initial estimates of expected energy extraction at different conditions.

REFERENCES

Dehkordi, E. S. and Schincariol, R. A.: Effect of thermal-hydrogeological and borehole heat exchanger properties on performance and impact of vertical closed-loop geothermal heat pump systems. Hydrogeology Journal, 22, (2014), 189-203.

Diersch, H.-J. G., Bauer, D., Heidemann, W., Rühaak, W., and Schätzl, P.: Finite element modeling of borehole heat exchanger systems Part 1. Fundamentals, Computer & Geosciences, 37, (2011a), 1122-1135.

Diersch, H.-J. G., Bauer, D., Heidemann, W., Rühaak, W., and Schätzl, P.: Finite element modeling of borehole heat exchanger systems Part 2.Numerical simulation, Computer & Geosciences, 37, (2011b), 1136-1147.

Ditlefsen, C, Balling, I.M., Højberg, A.L., Sørensen, L.T., Sørensen, I. Bjørn, H. and Balling, N.: Opsummerende projektrapport (D25) og Gudelines og anbefalinger (D23). Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice. Energiteknologisk Udviklings- og Demonstrations Program (EUDP), Copenhagen, (2014a).

Ditlefsen, C., Sørensen, I., Slott, M. & Hansen, M. 2014b: Estimation of thermal conductivity from existing soil descriptions. – A new web based tool for planning of ground source heating and cooling. GEOLOGICAL SURVEY OF DENMARK AND GREENLAND BULLETIN 31, (2014b), 55-58.

Højberg, A.L, and Rasmussen, P.: Modellering af varmetransport (D20). Energianlæg baseret på jordvarmeboringer – udvikling af markedsfremmende værktøjer og best practice. GeoEnergi. Energiteknologisk Udviklings- og Demonstrations Program (EUDP), Copenhagen, (2014).

Vandenbohede, A., Hermans, T., Nguyen, F. and Lebbe, L.: Shallow heat injection and storage experiment: Heat transport simulation and sensitivity analysis. Journal of Hydrology, 409, (2011), 262-272.

Acknowledgements

The authors would like to thank The Energy and development Program (EUDP) of The Danish Energy Agency for supporting this investigation.