Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Efficiency Increase of Soil Heat Exchangers due to Groundwater Flow and Air Injection Wells

Xiaolong Ma[1], Jürgen Grabe[2]

Hamburg University of Technology, Harburger Schlossstrasse 20, 21079 Hamburg, Germany

[1]xiaolong.ma@tu-harburg.de, [2]grabe@tu-harburg.de

Keywords: optimization, numerical simulation, energy pile, air injection well, groundwater flow

ABSTRACT

Geothermal Energy is available all over the world and plays an increasingly important role in the supply of renewable energy, especially in the heating and cooling sector. In order to collect geothermal energy, various soil heat exchanger systems have been established and developed in recent years. Thermal activated piles (energy piles) are one of the most efficient systems, since the cost of production can be reduced due to dual utilization. The heat production of energy piles depends on various factors. In soils with moving groundwater heat propagates much faster than without groundwater flow. However, the impact of groundwater on the heat output of energy piles has not yet been studied thoroughly. A numerical approach was utilized to simulate conductive and convective heat transfer between heat carrying fluid and the surrounding materials (tube, concrete, soil and groundwater). In addition to the investigation of groundwater impact, a patented optimization method for borehole heat exchangers – the air injection well -- is presented. It has been simulated numerically, in order to obtain an estimate of the theoretical efficiency.

1. INTRODUCTION

In Germany underground and groundwater temperatures up to 100 m depth are constantly between 8.5 °C and 12 °C. As this temperature is relatively stable over the whole year, it gives rise to the opportunity of heat extraction/injection for environmental and economical heating and cooling. Several variations of heat exchangers in the ground such as ground heat collectors, borehole heat exchangers and thermo-active ground structures have been installed worldwide over the past 20 years (Brandl 2006, Katzenbach et al 2008).

Energy piles are one of the most commonly employed thermo-active ground structures. Statically required piles are assembled with plastic U-tubes (seldomly with metallic tubes) and then filled with a heat transfer medium. During circulation of the heat transfer medium in the U-tubes, heat can be extracted or discharged from/into the ground. The double usage of piles enables a cost reduction during manufacture. Experience from many existing systems e.g. at Zürich Airport (Pahud and Hubbuch 2007) and in Sapporo City University (Nagano 2007) have shown the cost-effectiveness of energy piles.

In saturated soils, the heat transfer velocity and the therefore heat pruduction capacity of energy piles can be enhanced by groundwater flow. Numerical simulations are used to investigate the influence of groundwater flow (Ma and Grabe 2009-1).

Air injection wells are a commonly used decontamination method in saturated soils. As a result of air injection, artificial groundwater flow is induced, which can also be used to improve convective heat transfer in subsoils and therefore the heat production capacity of geothermal systems. Such a borehole heat exchanger combined with an air injection well is numerically calculated in order to investigate the effect on the efficiency.

2. HEAT TRANSFER IN GEOTHERMAL SYSTEMS

Heat transfer from the heat transfer medium to the soil/groundwater is a very complex thermodynamic process including conduction, convection and radiation (**figure 1**). Due to the low temperature and a minor temperature gradient, radiation can be neglected. Heat transfer in the U-tubes can be considered as convective, whereas the transfer from U-tubes to concrete is primarily conductive.

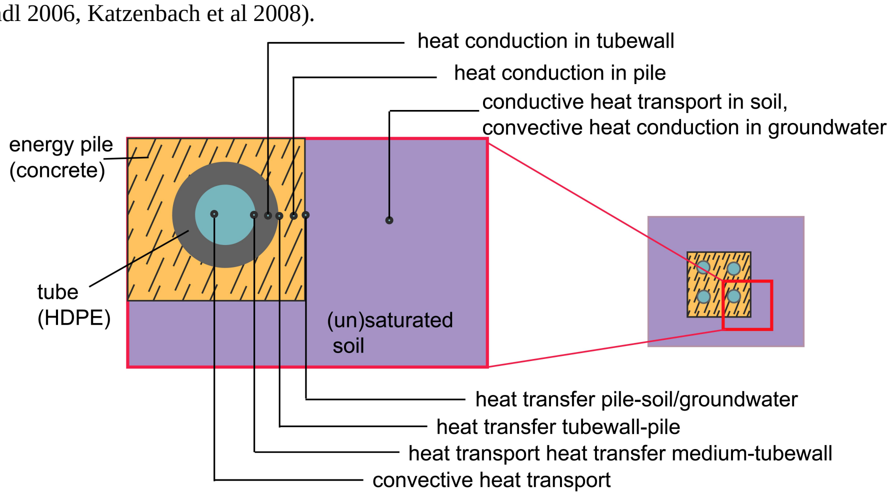

Figure 1: Mechanism of heat transfer in and around an energy pile with two U-tubes – section of energy pile with surrounding

The heat propagation in saturated soils is a combination of conduction and convection. If thermal properties like heat conductivity k, heat capacity c as well as heat sources do not depend on the temperature, the differential equation can be written as:

$$\overbrace{(\rho \cdot c)_{\text{soil}} \frac{\partial \vartheta}{\partial t}}^{\text{Time change}} = \overbrace{\text{div}(k \cdot \text{grad}\,\vartheta)}^{\text{Conduction}} - \overbrace{v \cdot \text{grad}\,\vartheta}^{\text{Convection}} + \overbrace{\dot{w}}^{\text{Heat scoure}}$$

ρ is the density of soil and v is the velocity field of groundwater.

3. NUMERICAL INVESTIGATION OF THE INFLUENCE OF GROUND-WATER FLOW

Numerical simulations of the influence of groundwater flow on energy piles have been performed on the basis of a pilot plant in the HafenCity Hamburg (Ma and Grabe 2007). A desiccant assisted air conditioning system using shallow geothermal energy has been built for the investigation of an ecological air conditioning system. The geothermal system consists of five energy piles and three heat exchange boreholes. Summer operation is considered, i.e. where the geothermal system is used for cooling.

3.1 Model Building

To minimize the computing time and using the planar symmetry of the pile, it is appropriate to simulate just one half of a rectangular energy pile with a Finite-Element model (**figure 2**). The pile length is 15 m. The soil body is 1 m deeper. The model is chosen to be longer in downstream direction of groundwater flow than in the upstream direction.

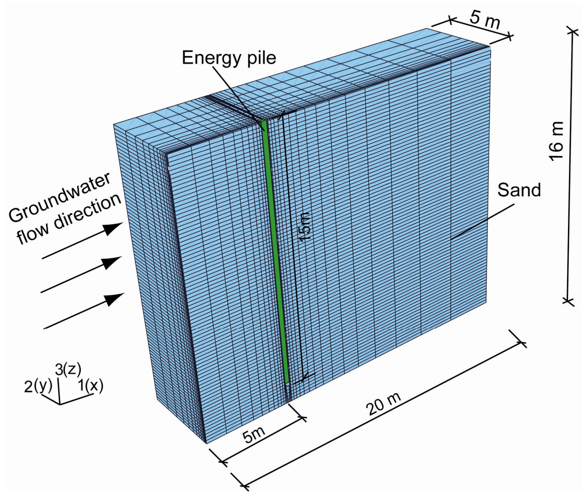

Figure 2: Planar symmetric 3D-Finite-Element system to investigate energy pile

Double U-tubes are fixed directly on the reinforcement cage. Outside of them is a 4 cm concrete covering, which protects both the reinforcement cage and the U-tubes. Concerning the planar symmetry, only one U-Tube is included in the half pile (**figure 3**). The U-tube consists of HDPE and has an outer diameter (d_o) of 2 cm and a wall thickness (e) of 0.19 cm (the HDPE tubes themselves are not modeled). For simplification of meshing, the round section of the tubs is simulated to be a rectangle. The equivalent length of the rectangle (L) is calculated as following:

$$L = \sqrt{\frac{\pi(d_o - 2 \cdot e)^2}{4}} = 1.44\,\text{cm}$$

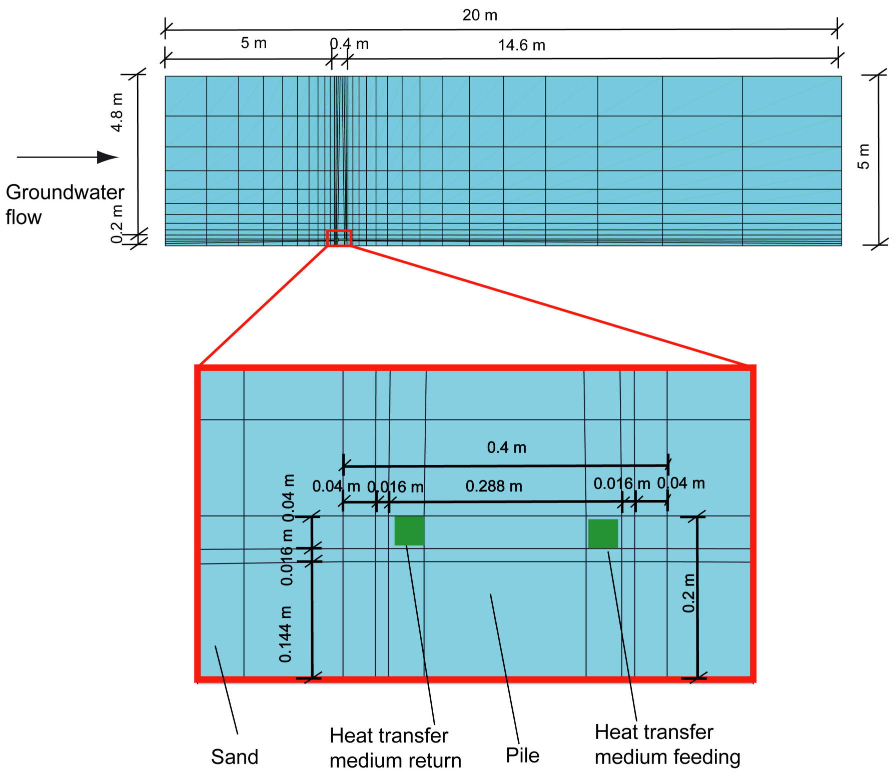

Figure 3: Top view of the 3D-Finite-Element system

The boundary and initial conditions for heat transfer are

$grad\,\vartheta = 0$ for all boundaries

$\vartheta(t = 0) = 10\,°C$.

Homogeneous and saturated sand with a quartz fraction (q) of 75% is used as soil material. The hydraulic and thermodynamic properties of sand and concrete are listed in table 1. Water is used as heat transfer medium in the tubes.

Table 1: Hydraulic and thermodynamic soil properties

Thermal conductivity (k)	2.53 W/(m•K)
Specific heat capacity (c)	1750 kJ/(kg•K)
Drainable porosity (n)	0.15
Density (ρ)	2100 kg/m³

Heat transfer through the energy pile into subsoil is driven by a chosen convection of the heat transfer medium in U-tubes (constant inlet temperature). The heat transfer is monitored over a period of 90 days.

3.2 Simulation Results

Without groundwater movement heat can only be transferred conductively. The temperature contours in horizontal planes are nearly half circles (**figure 4**). In the presence of groundwater flow, the heat is dissapated with the water. This convection boosts heat transfer velocity in soil and therefore the heat injection capacity of the energy pile. The temperature field for this case is no longer axially symmetric (**figure 5**). At a seepage velocity of v = 1.5 m/d, the heat cannot propagate upstream, since the convective part of the heat transfer dominates the conductive one. Almost all injected heat is carried downstream and forms a heat flag there.

The time dependent specific heat injection capacity P_s (**figure 6**) per pile meter ([W/m]) can be obtained with calculated inlet and outlet temperatures ϑ_0 and ϑ_r of fluid transfer medium by:

$$P_S(t) = \rho_w A v_w c_w \left(\vartheta_0 - \vartheta_r(t) \right) \quad (1)$$

where A is the inner cross section of the U-tubes, ρ the density, v flow capacity and c specific heat capacity of transfer medium (water).

Without groundwater flow, the energy pile provides an average specific heat injection capacity of approximately 42 W/m over 90 days. This value is smaller than the recommendation by VDI (VDI 2001), which is 65-80 W/m for borehole heat exchanges in saturated sand. However the diameter of the U-tubes used for borehole heat exchangers (usually 32 or 40 mm) are larger than for energy piles (20 mm).

The influence of groundwater can not be neglected, if the seepage velocity is greater than several decimeters per day. With increasing groundwater velocity this influence amplifies. At a very high seepage velocity of 7.5 m/d, the average heat injection capacity is increased almost fourfold compared to resting groundwater (**figure 7**).

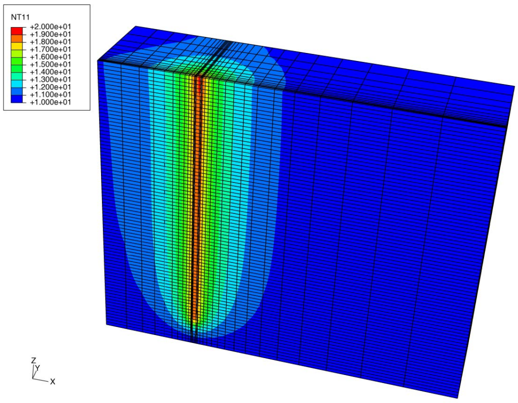

Figure 4: Calculated temperature field in soil after 90-days operation of energy pile without groundwater flow

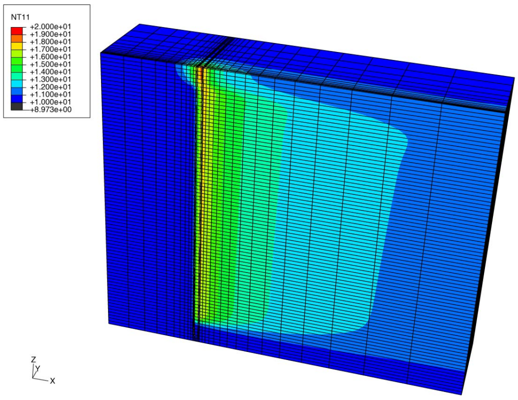

Figure 5: Calculated temperature field in soil after 90-days operation of energy pile with a seepage velocity of v = 1.5 m/d

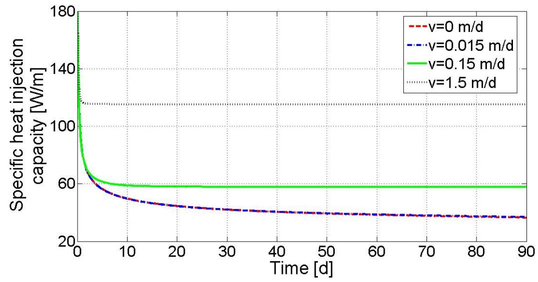

Figure 6: Calculated time dependent specific heat injection capacity of one energy pile for different seepage velocities

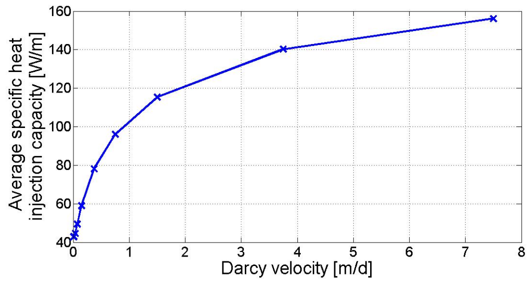

Figure 7: Calculated average specific injection capacity for different seepage velocities

4 ARTIFICIAL GROUNDWATER FLOW INDUCTION

Considering the fact that groundwater flow has a strong influence on the heat transfer in saturated soils, the question arises: how can the groundwater flow be induced artificially? Our European patent using air injection wells in geothermal energy systems (patent No.: 09101001.4-2301) is one possibility.

An air injection well is an in situ soil decontamination method for saturated soils. The operation induces a circulating flow in the aquifer due to the injection of pressurized air at the deepest point of a filter pipe (Luber 1999). If air injection wells are positioned near geothermal systems (**figure 8**), the artificial groundwater circulation can increase the heat transfer in the soil and thus the heat extraction/injection capacity. Air injection wells can also be combined with a heat exchange borehole (**figure 10**). In the region of aquifer, the borehole is not filled up with backfill materials and functions as a well. The tube for air injection is then located in this well. The exhaust air of the well has been cooled or heated and can, according to requirements, be used for feeding air conditioning / heating systems.

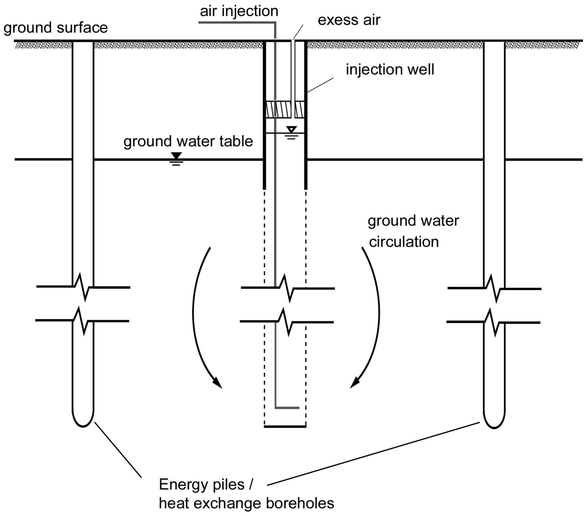

Figure 8: Principle of usage of air injection wells near a geothermal system

Air injection into a well generates a mixture of water and air having a lower density than the surrounding groundwater. In order to acquire a pressure equilibration, the table of the water/air mixture must be higher than the groundwater table (**figure 8** and **10**). Comparing the fluid pressure in the injection well with the aquifer, an over pressure dominates the upper region of the well, while a low pressure is generated at the bottom of the well (**figure 9**). The pressure difference causes the fluid at the top of the well to flow outwards and the groundwater is forced through the filter pipe into the well in the deeper region. Around the well a circulation is induced.

The usage of air injection wells can improve the efficiency of geothermal systems in the following ways:

• groundwater circulation enhances the convective heat transfer in the soil,

• circulation of water/air mixture in the well accelerates heat exchange between U-tubes and groundwater,

• feeding air to the air conditioning / heating systems is pre-cooled or pre-heated.

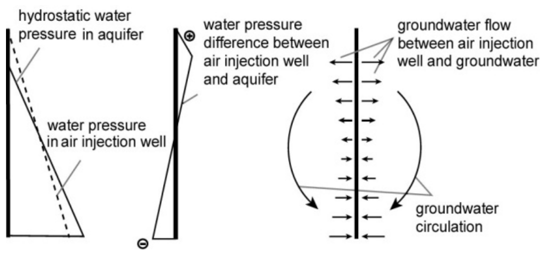

Figure 9: Distribution of water pressure and difference in air injection well and aquifer (left and middle), water flow direction (right)

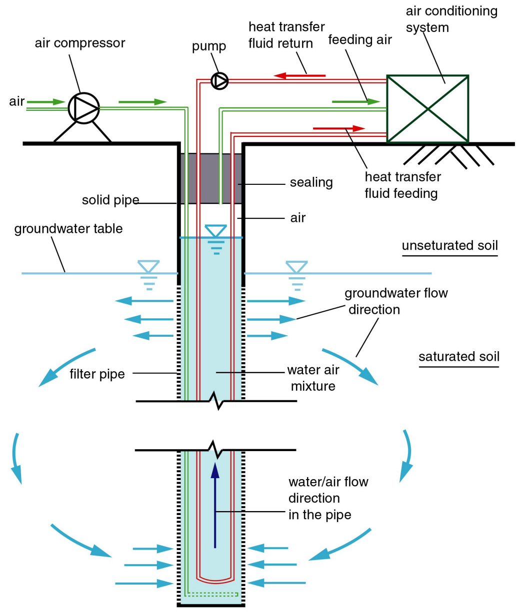

Figure 10: Combined air injection well with a borehole heat exchanger and air conditioning system

5. NUMERAICAL SIMULATION OF AN AIR INJECTION WELL

Numerical modeling (Ma and Grabe 2009-2) is based upon a combined air injection well with a borehole heat exchanger. The simplified system has a 10 m deep homogenous aquifer between two aquitards (**figure 10**). The pore space of the aquifer is saturated with unconfined groundwater. The borehole above and below aquifer is filled up with backfill material. Hence the air injection well can only influence groundwater flow and therefore heat transport in the aquifer layer, so the two aquitards are not components in the numerical model.

5.1 Model Building

Due to complexity, the heat distribution and 2-phase fluid flow within the air injection is not considered in the model. The air injection well is simplified as a cannulate cylinder, whose wall is a boundary of the system and has constant temperature and water pressure. The system is then axially symmetric and can be simulated with 2D-model.

In the first modelthe density of water/air mixture in a standard model is set to 900 kg/m³. Its table reaches 0.56 m above the surrounding groundwater table, in order to gain pressure equilibration. On the right side a hydrostatic water pressure governs the boundary. There is no water exchange on the right boundary as well as between aquifer and aquitards at the top and bottom of the model (**figure 12**).

Soil properties are taken from **table 1**. Hydraulic conductivity is assumed to 1•10^{-5} m/s.

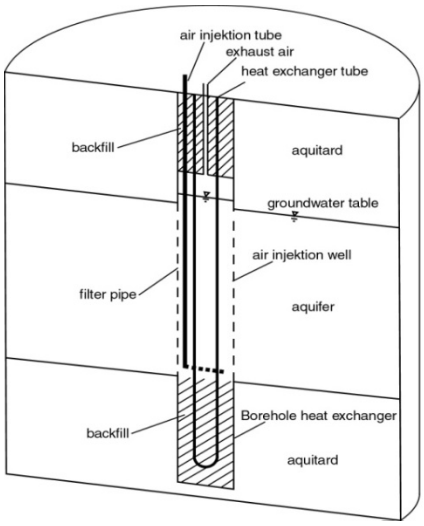

Figure 11: Considered system for the simulation of usage of air injection well in a borehole heat exchanger

The groundwater flow and heat transfer are simulated separately. In the first step, Darcy's law is used to calculate the circulation flow of groundwater induced by air injection well. After a steady state is achieved, the groundwater flow velocity field is maintained and imported into heat transfer model, which is monitored over a period of 90 days.

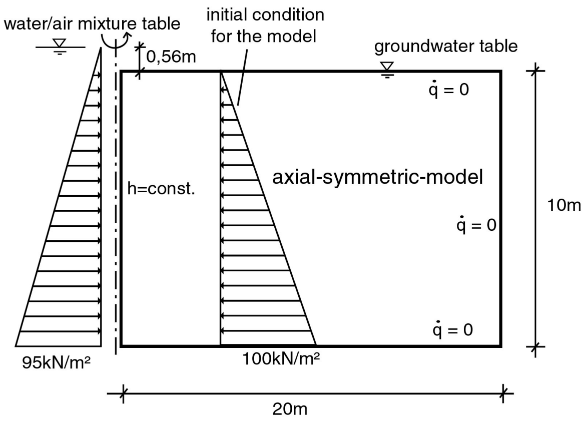

Figure 12: Axial-symmetric-model with boundary and initial conditions for Darcy's law

Summer operation is investigated using this model. The injection well is simplified as a cylindical heat source with a constant temperature implying that heat will be injected through the whole shaft surface of the borehole. This improves heat transfer velocity and causes an increasing heat injection capacity both for the models with and without the air injection well (Gehlin et al 2003). This effect is not relevant for the consideration of the relative efficiency increase if a relative increasing factor is used:

$$f_{aiw} = \frac{P_{s,aiw} - P_{s,no}}{P_{s,no}} \qquad (2)$$

where $P_{s,aiw}$ and $P_{s,no}$ are the average heat injection capacities with and without air injection well respectively.

The boundary and initial conditions for heat transfer of the model are:

$\mathrm{grad}\,\vartheta = 0$ for all boundaries except the wall air injecion well

$\vartheta = 20\,°\mathrm{C}$ at the wall air injecion well

$\vartheta(\mathrm{t} = 0) = 10\,°\mathrm{C}$.

5.2 Simulation Results

5.2.1 Groundwater Circulation

Originally, groundwater in the model does not flow, because there is no hydraulic gradient. After activation of air injection well, the higher table and lower density of water/air mixture in the well causes the pore water pressure to change on the left side of model. The fluid flow is calculated until steady state is reached.

The pressure on the upper region is elevated, while it's reduced on the bottom. This pressure change generates a groundwater circulation (**figure 13**).

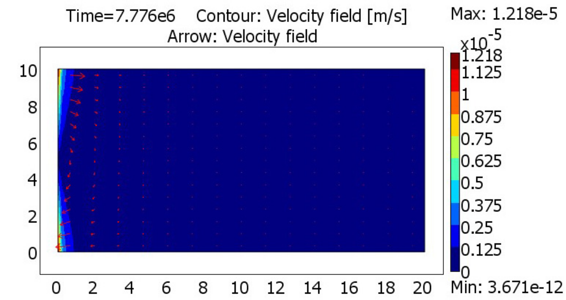

Figure 13: Groundwater flow velocity field around an air injection well

The maximum flow velocity (ca. 1.2•10^{-5} m/s) in the basis model appears outside of the well-top and -bottom. It declines rapidly with increasing distance to the well. The arrows show the flow direction. Water flows out of the well from the upper region and then in the tracing of half ellipse to the bottom and from there into the well again.

5.2.2 Heat Propagation in Subsoil

With resting groundwater, heat can only be transferred conductively. Due to constant thermodynamic soil parameter, the contour of temperature is homogenous (Figure 14).

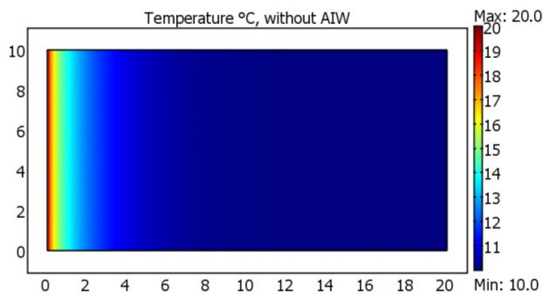

Figure 14: Temperature field without air injection well after an heat injection period of 3 months

The induced groundwater circulation as a result of the activated air injection well increases convective heat transfer in subsoil. **Figure 14** shows the temperature field after a period of 90 days. In the upper region, heat propagates with flowing groundwater down right. The transfer velocity is higher than only with conduction. On the lower region, groundwater flows towards the well. Convective heat transfer is in opposite direction of conduction. Therefore heat propagation in this region is slowed down.

Comparing **figure 14** and **15** it is apparent that the total injected heat is more with air injection well than without it.

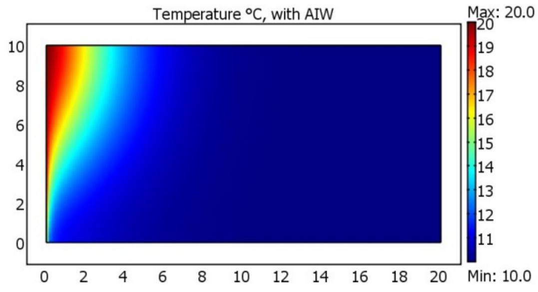

Figure 15: Temperature field with air injection well after an heat injection period of 3 months

5.2.3 Heat Injection Capacity

The total injected surface heat quantity $e_h(t)$ in kWh/m after a certain time t can be calculated using the equation:

$$e_h(t) = \int_{\Omega} \rho c[T(t) - T_0] dA \qquad (3)$$

where T is the temperature, dA is the element area. The volume heat quantity $E_h(t)$ in kWh can be deduced from the integration of axial-symmetric-model to 3D-model. The specific heat injection capacity $P_s(t)$ is a time dependent value. It can be computed with the equation

$$P_s(t_n) = \frac{E_h(t_n) - E_h(t_{n-1})}{l \cdot (t_n - t_{n-1})} \qquad (4)$$

where l is the length of the borehole heat exchanger in the aquifer. **Figure 5** shows the time dependent specific heat injection capacity of the borehole heat exchanger. Under continual operation, the temperature difference between borehole wall and surrounding soils decreases with time and therefore the injection capacity. The influence of air injection well (AIW) on the heat injection capacity increases in the first days and then remains almost constant.

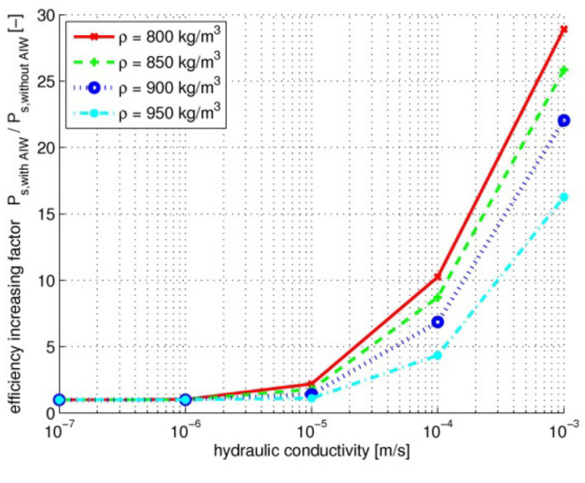

Figure 16: Calculated time dependent specific heat injection capacity with and without air injection well over a period of 90 days

The numerical simulations show that under the above-mentioned condition, the relative increasing factor f_{aiw} amounts 50%.

Several variations of the calculations, with different hydraulic conductivities and water/air mixture densities, were also performed. The relative efficiency increasing factor f_{aiw} is presented in **figure 17**. At a hydraulic conductivity (k_f) smaller than 10^{-6} m/s, the installation of air injection well does not lead to any significant advantage. With growing hydraulic conductivity the influence of air injection well increases. In middle sand, which has a typical k_f of 10^{-4} m/s, the heat injection rate can be enhanced up to 2800%.

A lower density of water/air mixture in the injection well causes larger pressure difference on the surface of the well, which results in faster groundwater circulation and therefore a higher efficiency increasing factor. On the other hand, more energy will be needed for the air injection pump to gain a lower density of water/air mixture.

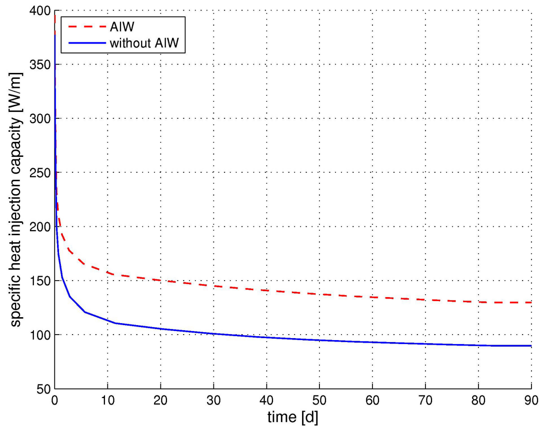

Figure 17: Dependence of calculated relative efficiency increasing factor on hydraulic conductivity and water/air mixture density

6 CONCLUSIONS

The heat transfer and groundwater flow has been calculated using a numerical method. The results indicate that the influence of groundwater cannot be neglected for seepage velocities greater than several decimeters per day. At a very high seepage velocitiy of 7.5 m/d, the specific heat extraction/injection capacity is increased almost fourfold. This implies that the groundwater flow should also be considered in the estimation of heat injection/extraction capacity of energy piles.

The fluid flow and heat transfer of a borehole heat exchanger combined with an air injection well has been calculated sequentially using the package Earth Science of the Finite-Element-Code COMSOL. The equation of Darcy's Law was first solved to achieve the groundwater circulation velocity under steady state conditions as a result of the activation of air injection well. In the second step, the maintained flow velocity was imported as initial condition for the transient heat transfer simulation.

The results of the simulations show that the combination of air injection well in borehole can improve the heat injection capacity vastly. Laboratory and field tests are planned, in order to verify the numerical results.

ACKNOWLEDGEMENTS

Special thanks are given to the Federal Ministry of Economics and Technology of Germany and the Free and Hanseatic City of Hamburg, who support the research project.

REFERENCES

Brandl, H.: Energy Foundations and Other Thermo-Active Ground Structures, *Geotechnique*, **56 (2)**, (2006), 81-122

Gehlin, S., Hellström, G. and Nordell, B.: Comparison of four models for thermal response test evaluation, *ASHRAE Transaction*, **109**, (2003), 131-142

Katzenbach, R., Vogler, M. and Waberseck, T.: Large energy pile systems in urban areas, Bauingenieur, **83**, (2008), 343-348

Luber, M.: Luftinjektionsbrunnen zur in situ Grundwassersanierung, Hydraulik und Stoffdurchgang, Institut für Bodenmechanik und Felsmechanik der Universität Karlsruhe, **Heft 47**, (2008)

Ma, X., and Grabe, J.: Nutzung der oberflächennahen Geothermie in der HafenCity. *Proceedings,* 74. Tagung der Norddeutschen Geologen, (2007), 59-60

Ma, X., and Grabe, J.: Influence of Ground-water Flow on Efficiency of Energy Piles, *Proceedings*, Int. Conf. on Deep Foundations - CPRF and Energy Piles, Frankfurt, (2009-1)

Ma, X., and Grabe, J.: Modeling of Usage of Air Injection Well in a Geothermal System, *Proceedings*, COMSOL Conference, Hannover, (2009-2)

Nagano, K.: Energy Pile System in New Building of Sapporo City University. *In "Thermal Energy Storage for Sustainable Consumption"*, Springer (2007), 245-253

Pahud, D., and Hubbuch, M.: Measured Thermal Performance of the Energy Pile System of the Dock Midfield at Zürich Airport. *Proceedings*, European Geothermal Congress, Unterhaching, Germany, (2007)

VDI. Thermal use of the underground - Ground source heat pump systems. *Verein Deutscher Ingenieure* (VDI), Guideline 4640-2, (2001)