New Developments in near-surface geothermal energy systems

Nouveaux Développements dans les systèmes géothermiques proches à la surface

Ziegler M., Kürten S.
Geotechnical Engineering, RWTH Aachen University

ABSTRACT: The geothermal utilization of the ground is a future oriented and environmental option to gain heat. In most cases borehole heat exchangers (BHE) are used. However, in the last years several researches which focussed on the development of new technologies are carried out. The Chair of Geotechnical Engineering (RWTH Aachen University) investigated new applications for the near-surface geothermal energy sector. In this regard, the geothermal utilization of smouldering mining dumps as well as the development of thermo-active seal panels are two main research topics. For both systems the description of the heat transfer between the geothermal system and the ground are important for an effective plant design. Mostly, the existing calculation models are based on the formulation of thermal resistances. For symmetric systems (such as a BHE) several approaches exist. However, these approaches cannot be transferred to plane structures directly. Therefore, a new model for plane structures is presented in this paper.

RÉSUMÉ : L'utilisation géothermique du sol est une option environnementale et orientée vers le futur pour obtenir de la chaleur. Dans la plupart des cas on utilise des sondes géothermiques; cependant, dans ces dernières années, plusieurs recherches orientées vers le développement de nouvelles technologies ont été réalisées. Le Département de l'Ingénierie Géotechnique (RWTH Aachen University) a fait des recherches sur des nouvelles applications pour le secteur de l'énergie géothermique proche à la surface. À cet égard, l'utilisation géothermique de terril couvant, ainsi que le développement de panneaux thermoactifs scellés sont deux des principaux thèmes de recherche. Pour tous deux systèmes, la description du transfert de la chaleur entre le système géothermique et le sol est importante pour une conception effective de l'équipement. La plupart des modèles de calcul existants sont basés dans la formulation de résistances thermiques. Pour des systèmes symétriques (comme un BHE) il y a de nombreuses approches. Pourtant, ces approches ne peuvent pas être transférées directement à des composants de grande étendue. Un nouveau modèle pour des composants de grande étendue est présenté dans cet exposé.

KEYWORDS: Geothermal Energy, Heat Transfer, Earth-Coupled Structures, Thermal Resistance, Numerical Simulation.

1 INTRODUCTION

The use of geothermal energy has been increased over the past years in Europe. Mostly, borehole heat exchangers (BHE) or horizontal ground heat exchangers (horizontal loops) are installed in the ground to gain heat. In some cases existing earth-coupled structures are thermally activated, e.g. piles, diaphragm walls or ground slabs (e.g. Brandl 2006). New developments focus on the thermal utilization of underground structures especially tunnels (e.g. Pralle et al. 2009, Adam and Markiewicz 2009). The main advantage of these systems are the low installations costs comparing to common geothermal systems due to the combination of structural and geothermal elements.

At the chair of Geotechnical Engineering at RWTH Aachen University new applications for the geothermal use of the ground are investigated. The geothermal utilization of smouldering mining dumps as well as the development and testing of new thermo-active seal panels are two main fields of research. For both systems an integrated approach has been carried out to enlarge the efficiency of respective systems.

In this paper the two research topics will be introduced. Furthermore, suitable models for the description of the heat transfer between the geothermal system and the ground will be shown for each topic.

2 GEOTHERMAL UTILIZATION OF SMOULDERING MINING DUMPS

Mining dumps are a common occurrence in coal-mining areas. Less well known is the fact that in many old dumps smouldering fires exist. Due to a poor processing technique in the past the amount of residual coal is high. In conjunction with a low compaction spontaneous combustion occurs.

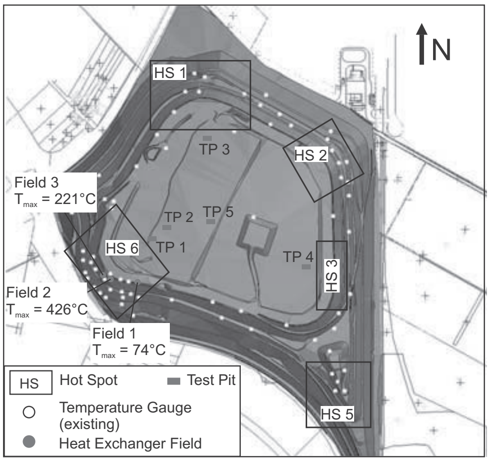

Figure 1. Schematic view of the smouldering mining dump

The smouldering leads to high temperatures inside the dump. These high temperatures imply a high energy potential, which isn't utilized until now. For determining the possible heat output from a smouldering a pilot plant on a mining dump in the 'Ruhr Area' in the western part of Germany has been operated over three years. An overview of the dump and the pilot plant is shown in Figure 1.

Three heat exchanging fields have been installed. Each field consists of a borehole heat exchangers (BHE) - designed as a coaxial probe – and five temperature measuring gauges, arranged in a semicircle around the BHE. Additional information on the plant can be found in Kürten et al. (2010). The heat exchanging fields were placed in a known Hot Spot (HS 6 in Figure 1). The maximum temperatures in each field varied between 75 °C (field 1) and 430 °C (field 2). The maximum values occurred in about 15m depth. So, the high energy potential of the dump can be confirmed.

Several Thermal Response Tests (determining the short-term behaviour of the plant, see e.g. Gehlin 2002) as well as long-term test were carried out. Additional, numerical simulations and analytical investigations were performed for estimating the main influencing parameters for the heat output. It could be shown, that a total heat output for the plant of 8kW could be achieved (Kürten et al. 2010). This corresponds to a heat requirement of two single family houses in Germany, approximately.

3 THERMO-ACTIVE SEAL PANELS

Based on the principle of thermo-active earth-coupled structures (e.g. Brandl 2006) thermo-active seal panels have been developed by the Chair of Geotechnical Engineering at RWTH Aachen University. For this, the required heat exchanging pipes were integrated in concrete protection plates made of PE-HD (PolyEthylene with High Density). Due to the thin plate the elements are characterized by a nearly contact to the ground. Furthermore, the wiring of the heat exchanging pipes is very flexible. The principle of the thermo-active seal panels is shown in Figure 2.

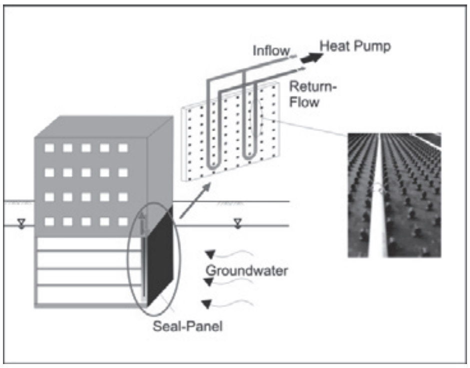

Figure 2. Principle of the thermo-active seal-panel

The main applications for the thermo-active seal panels will be underground structures with direct contact to groundwater. In this case a sealing of the structure is necessary anyway. By thermal activation of the system two functions (sealing and energetic function) can be combined. So, the additional installations costs for the geothermal plant are relatively low comparing to a common BHE.

The efficiency of the thermo-active seal panels was tested in large scale laboratory tests under different condition. The determined heat output varied between 30 W/m² and 300 W/m², whereby the higher values correspond to high flow rates in the heat exchanging system. The reason for this is that higher flow rates lead to a turbulent flow in the pipes and thereby to a better heat transfer between fluid and pipe. Additional, the thermal resistance of the system was measured approximately. The achieved values varied between 0.03 (mK)/W and 0.3 (mK)/W depending on the boundary and system conditions. According to the heat output the lowest values (optimum) belong to high flow rates.

In the laboratory tests different boundary conditions and system conditions were tested. The results have shown, that the decisive parameters for the heat output are the heat transmission area (characterized especially by the pipe distance, the leg distance between inflow and return flow and the pipe diameter), the flow rate in the heat exchanging system and the soil conditions (especially soil type, temperature, groundwater). More details can be found in Kürten et al. (2012).

4 HEAT TRANSFER BETWEEN GEOTHERMAL SYSTEM AND SUBSOIL

4.1 *Fundamentals*

For the planning and design of near surface geothermal plants the possible heat output of the systems for the existing boundary conditions has to be known. Empirical values are documented in the German guideline VDI 4640-2 (2009). These values are only valid for borehole heat exchangers and small installations (up to 30kW) as well as homogeneous conditions. For any other cases numerical simulations are necessary to guaranty a high efficiency of the system. Direct simulations (finite element methods, finite difference methods, etc.) are complicated and computationally very demanding. The reason is that the necessary scale (in time and space) for the explicit simulation of the heat exchanger and the simulation of the heat transport in the soil is different in a large order of magnitude. So, new methods are needed to reduce simulation time and the complexity of the model without losing accuracy.

One idea, which often has been used in the last years, is the transformation of the different processes to thermal resistances. The different thermal resistances can be superposed to a total thermal resistance. Then, the heat flow between geothermal system and soil can be calculated as the product of the total thermal resistance and the effective temperature difference. For the overall system the difference between soil and fluid temperature has to be used.

The difficulty in describing the heat transfer from the soil and the geothermal systems is therefore coupled to the accurate formulation of the total resistance of the systems. This value has to be formulated for each system depending on the relevant conditions. In the following the approach used for the BHE as well as the principles of a new model for plane structures developed by the authors will be shown.

4.2 *Heat transfer model for BHE*

In common literature many calculation models for the thermal resistance of a symmetrical system (such as BHEs) are documented and implemented in several software programs. Most of them are based on the work of Hellström (1991) as well as the applied model for determining the decisive parameters for the heat output from smouldering. A detailed model description can be found in Mottaghy and Dijkshoorn (2012). In the model the BHE is assumed as a 1D-Line-Element, which is integrated in a Finite-Difference-Mesh. The processes inside the BHE are modelled with the help of thermal resistances. The coupling with the software program is realized by passing over temperature boundary condition and heat flow rates. The model is implemented in the Finite-Difference-Program SHEMAT (Simulator for heat and mass transfer, see Clauser 2003). The program can simulate coupled heat and mass transfer (e.g. groundwater flow) and it has been proven for the simulation of geothermal systems.

Fundamentally, the thermal resistance for a coaxial probe depends on the pipe-diameter (inner and outer pipe), the pipe material, the flow rate, the heat exchanging medium and the backfill material (s. Figure 3). The main heat transport mechanisms are conduction (in the backfill material as well as in the inner and outer pipe) and convection (in the fluid). The conduction depends mainly on the material properties (characterized by the thermal conductivity) whereas the convection depends on the flow rate and the properties of the fluid (especially viscosity and density).

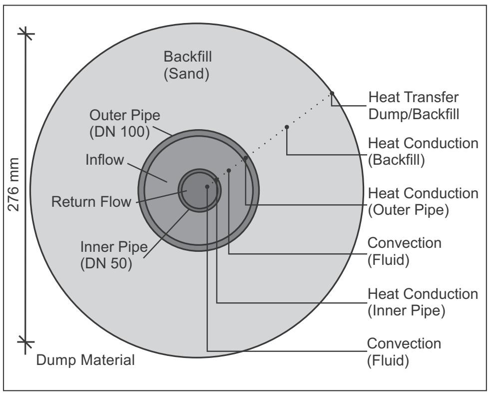

Figure 3. Heat transfer processes for the coaxial probe installed in the smouldering dump.

Every existing transport mechanism can be described with the help of thermal resistances. The different resistances can be combined with a series connection to a total connection and a total thermal resistance respectively. Details for the coaxial probe can be found in Mottaghy and Dijkshoorn (2012).

Post-test calculations of the in situ tests were performed to calibrate the applied model. After that, several analyses were carried out to identify the most important parameters for the geothermal utilization of a smouldering. As an example the influence of the thermal conductivity of the dump and the backfill material for each BHE is shown in Figure 4. The differences between the BHEs are caused by the different temperature regimes in the heat exchanging fields (see Figure 1). It can be seen that the thermal conductivity of the dump material is the most important parameter. In contrast, increasing the thermal conductivity of the backfill material has a less important influence.

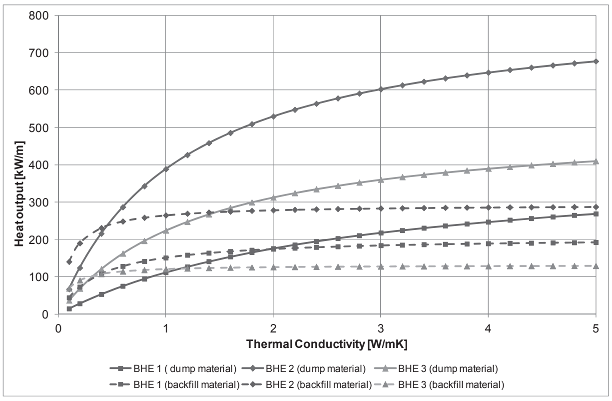

Figure 4. Influence of the thermal conductivity (dump and backfill material) for the heat output

The thermal conductivity of the existing dump material was determined in the laboratory. As a result, a value of 0.4 W/(mK) can be assumed. As expected the thermal conductivity of the material is very low. Additional, Thermal Response Tests (TRT) were carried out for each BHE. The resulting effective thermal conductivities varied between 1.0 W/(mK) (field 3) and 2.2 W/(mK) (Kürten et al. 2009). The effective thermal conductivity obtained by the TRTs cannot be equated with the thermal conductivity as a material property. It is rather a combination of all thermal processes involved. For the geothermal utilization of a smouldering the high underground temperature and the thermal radiation must be taken into account. For transferring the results to another site, the determining of the correct effective thermal conductivity will be the main problem.

In summary, the heat transfer inside the dump (heat replenishment) is the limiting factor the geothermal utilization of a smouldering. This is the reason why the achieved heat output of the pilot plant is relatively low comparing to the high temperatures inside the dump. Nevertheless, by the presented research project it could be shown that geothermal utilization of smouldering mining dumps is possible.

4.3 *Heat transfer models for plane structure*

For symmetric systems such as a BHE several approaches for the calculation of the heat transfer between ground and soil with the help of thermal resistances exist. In contrast, for plane structures there are no equivalent approaches documented. This may be due to the fact that the occurring processes are more complex due to the missing rotation-symmetry.

The developed thermo-active seal panels are characterized by a plane heat transfer. Nevertheless, in dependency of the boundary conditions the possible heat output of the systems must be describes realistically for an effective plant design. For this, a calculation model, which will be also implemented in the software program SHEMAT, has been developed by the Chair of Geotechnical Engineering at RWTH Aachen University.

The basic principle of the new calculation model corresponds to the existing model for a BHE (see section 4.2). The processes inside the thermo-active structure will be summarized to a total thermal resistance. The coupling between SHEMAT and the calculation model will be realized by passing over temperature boundary conditions and heat flows.

For the development of the calculation model two main aspects have to be considered. On the one hand, the heat transfer isn't symmetric. The heat transfer from the ground to the heat exchanging system should be the priority flow. Heat flows from the room have to be minimized to avoid a thermal circuit. On the other hand, the inflow and the return flow of the heat exchanging pipes are spatially separated. This means, that for a numerical simulation the heat exchanging systems cannot be design as a 1D-dimensional line-element only but rather as a 2D-dimensional element.

For determining the total thermal resistance for a plane structure the involved processes must be separated. The decisive single processes are shown in Figure 5.

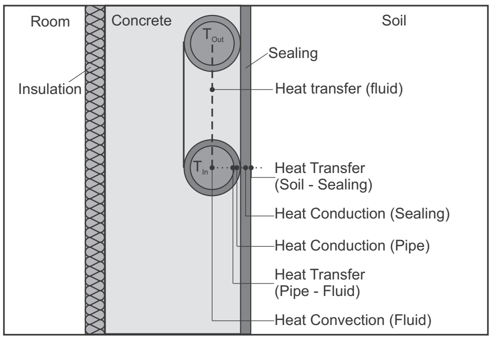

Figure 5. Heat transfer for a plane structure - thermal processes involved

The single processes can be transferred to a thermal resistance model (see Figure 6). It can be seen that there are three determining heat flows: heat flow due to the temperature difference between the two sides of the wall and the heat flow due the temperature difference between heat exchanger and ground and the room respectively. According to the superposition principle the two heat flows can be overlapped. The existing triangle mesh of the thermal resistances can be simplified to a star-network (see Figure 7).

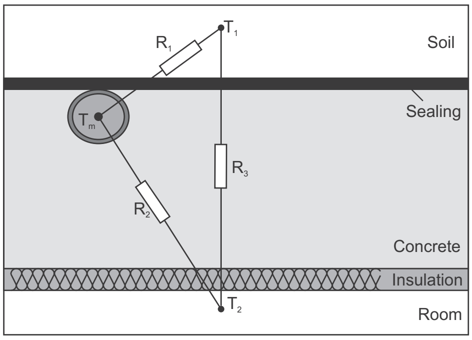

Figure 6. Thermal Resistance Model for the thermo-active seal panel (triangle mesh)

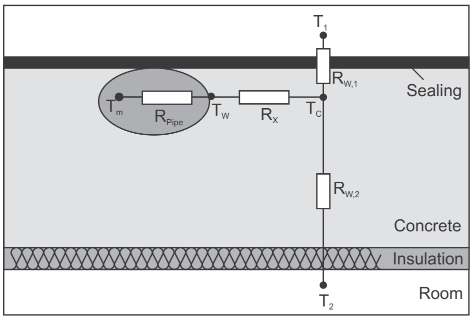

Figure 7. Thermal Resistance Model for the thermo-active seal panel (star-network)

The temperature in the heat exchanging pipe is assumed as an average temperature T_m between inflow and return flow. This simplification is very common in geothermal analyses. The thermal resistances due to the conduction in the pipe and the convection in the fluid flow are summarized to the resistance of the pipe R_{Pipe}. This leads to the temperature at the pipe wall T_W.

The interaction between the single heat exchanging pipes is represented by the so called ‘structure resistance’ R_x. Therefore, an approach will be taken which is adapted from the calculation of concrete core activation (see also Koschenz & Dorer 1999). By solving the differential equation for the heat conduction, the temperature distribution between two pipes can be determined. Then, the ‘core temperature” T_C can be calculated as an integral of the temperature distribution. In this context, the decisive parameters will be the pipe distance, the embedded material (concrete) and the position of the pipe (overlaying material).

The advantage of this procedure is that all processes which are connected to the heat exchanging pipes can be summarized by calculation the core temperature. After calculation the core temperature the heat flow to both sides of the wall can be determined by using the well known assumption for the 1D-heat transfer through a wall. For the numerical coupling this approach has another advantage. The parameters which are used in the calculation model are the same values as the transfer values for SHEMAT (heat flows through both side of the wall and the resulting temperature at the outside of the wall T_1 and T_2 respectively).

5 CONCLUSION AND OUTLOOK

Near Surface Geothermal Energy is a good alternative to satisfy the heat requirement of buildings. To improve the efficiency of this renewable energy resource, new systems must be developed. It was shown that the thermal utilization of smouldering mining dumps is possible. The limiting factor is the poor transport inside the dump (due the low thermal conductivity) which can be compensated by the high temperature only for a bit. Nevertheless, the thermal utilization of the smouldering is a good alternative for the owner of the dump to deal with the smouldering.

The thermal activation of earth coupled structures is principle available for everyone. From the economic point of view, the boundary conditions (soil type, underground temperature, contact area, etc) have to be favourable. To achieve a high efficiency of this systems the heat transfer between soil and heat exchanger as to be described accurately. A calculation model for describing the heat transfer for plane structures between ground and thermo-active structures has been developed by the Chair of Geotechnical Engineering at RWTH Aachen University. This model is based on the combinations of thermal resistances, which is a common method in geothermal analyses. The model will be implemented in the software program SHEMAT. After that the calculation model should be verified by numerical simulations and calibrated with laboratory tests.

6 ACKNOWLEDGEMENTS

The research on the utilization of smouldering mining dumps was funded by the Federal Ministry of Education and Research (Germany). The work was done in collaboration with Unit of Technology of fuels (RWTH Aachen University, Germany), Fraunhofer Institute UMSICHT (Oberhausen, Germany), DMT – Department of Fire Protection (Dortmund, Germany) and Aix-o-therm GeoEnergien (Marl, Germany). The development of a Software tool for the calculation of the heat transfer of plane structures is funded by Deutsche Bundesstiftung Umwelt (DBU). This work is done in collaboration with Geophysica Beratungsgesellschaft mbH (Aachen, Germany) and NAUE GmbH & Co.KG. Sincere thanks are given to all.

7 REFERENCES

Adam D. and Markiewicz R. 2009. *Energy from earth-coupled structures, foundations, tunnels and sewers*. Géotechnique 59(3), 229-236.

Brandl H. 2006. *Energy foundations and other thermo-active ground structures*. Géotechnique 56(2), 81-122.

Clauser, C. 2003. *Numerical Simulation of Reactive Flow in Hot Aquifers. SHEMAT and Processing SHEMAT*. New York, Springer.

Gehlin, S. 2002. *Thermal Response Test – Methods, Development and Evaluation*. Ph.D. Thesis. Dep. of Environmental Engineering, Lulea University of Technology, Sweden.

Hellström, G. 1991. Ground heat storage. Thermal analysis of duct storage systems. Ph.D. Thesis; Dep. of Mathematical Physics, University of Lund, Sweden.

Koschenz, M., Dorer, V. 1999. *Interaction of an air system with concrete core conditioning*. Energy and Building 30, 139-145.

Kürten, S.; Ziegler, M.; Olischläger, V.; Ehrenberg, H. 2012. Untersuchungen zur Effizienz von thermo-aktiven Abdichtungs-elementen zur thermischen Nutzung des Untergrunds. In: Bautechnik 89 (3), p. 192-199.

Kürten, S., Feinendegen, M., Noel, Y., Gaschnitz, R., Schwerdt, P., Klein, A. 2010. *Geothermal Utilization of Smouldering Mining Dumps as a Substitute for Fossil Fuels*. Proceedings of ICCFR2 - Second International Conference on Coal Fire Research, Berlin, Germany.

Mottaghy, D. and Dijkshoorn, L. 2012. *Implementing an effective finite difference formulation for borehole heat exchangers into a heat and mass transport code*. Renewable Energy 45, 59-71.

Pralle N., Franzius J.N., Acosta F., Gottschalk D. 2009. *Using Tunneling Concrete Segments as Geothermal Energy Collectors*. Proceedings of the 5th Central European Congress on Concrete Engineering. Baden, Germany. 137-141.

VDI 4640-2 2009. *Thermal use of the underground – Ground source heat pump systems*. Beuth-Verlag, Berlin, Germany.