Geophysical Research Abstracts
Vol. 18, EGU2016-18084, 2016
EGU General Assembly 2016

Borehole Heat Exchanger Systems: Hydraulic Conductivity and Frost-Resistance of Backfill Materials

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Ground source heat pump (GSHP) systems are economic solutions for both, domestic heating energy supply, as well as underground thermal energy storage (UTES). Over the past decades the technology developed to complex, advanced and highly efficient systems. For an efficient operation of the most common type of UTES, borehole heat exchanger (BHE) systems, it is necessary to design the system for a wide range of carrier fluid temperatures. During heat extraction, a cooled carrier fluid is heated up by geothermal energy. This collected thermal energy is energetically used by the heat pump. Thereby the carrier fluid temperature must have a lower temperature than the surrounding underground in order to collect heat energy. The steeper the thermal gradient, the more energy is transferred to the carrier fluid. The heat injection case works vice versa.

For fast and sufficient heat extraction, even over long periods of heating (winter), it might become necessary to run the BHE with fluid temperatures below 0°C. As the heat pump runs periodically, a cyclic freezing of the pore water and corresponding ice-lens growth in the nearfield of the BHE pipes becomes possible. These so called freeze-thaw-cycles (FTC) are a critical state for the backfill material, as the sealing effect eventually decreases. From a hydrogeological point of view the vertical sealing of the BHE needs to be secured at any time (e.g. VDI 4640-2, Draft 2015). The vertical hydraulic conductivity of the BHE is influenced not only by the permeability of the grouting material itself, but by the contact area between BHE pipes and grout.

In order to assess the sealing capacity of grouting materials a laboratory testing procedure was developed that measures the vertical hydraulic conductivity of the system BHE pipe and grout. The key features of the procedure are:

- assessment of the system′s hydraulic conductivity
- assessment of the system′s hydraulic conductivity after simulation of freeze-thaw-cycle
- constant radial stress boundary conditions (sigma 2 = sigma 3 = constant)
- radial freezing from inside out, following the in-situ freezing direction

The results differ substantially from prior test procedures (such as standardized frost tests for concrete or soft soils). Concentric frost-induced cracking was observed. The cracking pattern is in good agreement with cryostatic suction processes and frost heave in fine grained soils. The hydraulic conductivity of the system depends on the composition of the grout. With the developed testing device (and procedure) a unified and independent assessment and quality control becomes feasible. Adequate materials for advanced shallow geothermal systems can be clearly identified.