Abstract
論文の内容の要旨

Title of Dissertation:
Experimental and Numerical Study on Thermal Response Test for Design Accuracy Improvement of Vertical Closed-loop Ground Heat Exchanger

論文題目:
（垂直密閉型地中熱交換器の設計精度向上のための熱応答試験に関する実験的、数値的研究）

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The vertical closed-loop borehole heat exchanger (BHE) is a type of ground heat exchanger, which is a key component of ground-source heat pumps (GSHPs). The design of a vertical closed-loop borehole heat exchanger requires the effective thermal conductivity of the ground and the borehole thermal resistance to be determined. During the design of a large borefield, an in situ thermal response test (TRT) is conducted to obtain reliable values for these parameters. Because the TRT setup is fully exposed to the outdoor environment, disturbances occur that can increase the error in the results. Although many new TRT and interpretation methods have been suggested, the actual practice remains the same: injecting a constant heat rate and interpreting the response data with the infinite line source (ILS) model. This is due to the high level of difficulty and greater cost of the new methods compared to the conventional method. If experimenters stay with the conventional TRT method, they should at least be equipped with comprehensive guidelines or literature that provides insights into conducting TRTs and designing the TRT

setup to obtain quality data. This is the starting point of this thesis.

As an inverse problem, the TRT should satisfy the following two requirements for reliable estimation: (1) the assumptions made in the physical model (e.g., analytical or numerical) used for the inverse estimation and the experimental conditions should be consistent, and (2) the physical model should appropriately represent actual physical phenomena.

The former is with regard to the disturbances to the TRT and the resulting inconsistency between the assumptions of the physical model and the experiment. Because of the heat exchange between the surrounding environment and the TRT setup, the constant heat rate assumption of the ILS model is violated. This perturbs the temperature response, which leads to an estimation error. The latter is with regard to if the physical model can properly reflect the actual heat transfer process in the ground. Specifically, the effect of natural convection in a saturated porous formation leads the TRT results to show a heat rate dependence, which generally has been not considered or neglected.

The first half of this thesis addresses the disturbance problem. First, an analytical model that describes the heat exchange between the circulating fluid and outdoor environment in an aboveground TRT setup was derived. Based on the derived model, a parametric study and sensitivity analysis were conducted in a systematic manner using disturbance-related parameters, such as the test settings (heat injection rate and flow rate), aboveground connecting circuit parameters (insulation thickness, length, and radiation absorptivity), temperature of fluid, and weather conditions (solar irradiation, environmental temperature, and wind velocity). Based on the results, suggestions are provided for experimenters on designing TRT setups and conducting TRTs to obtain quality data.

Second, the effect of disturbances from the outdoor environment on TRT interpretation using the ILS model was quantitatively examined with numerical methods. The derived analytical model considering disturbances was incorporated as the boundary condition of a numerical model. Typical synthetic weather data of different seasons and 36 cases of measured weather data were used to numerically conduct and interpret TRTs. Some characteristic interpreted behaviors related to weather conditions were explained. Based on the 36 cases of numerical TRTs, changes in the error range with the TRT duration were analyzed to clarify the applicability and limitations of conventional interpretation using the ILS model. Some practical suggestions regarding the performance and interpretation of TRTs are provided.

Lastly, as a solution to interpreting disturbed TRT data and to utilize additional information from the sequential estimation method, an alternative method is proposed using a temporal superposition-applied ILS model combined with the quasi-Newton optimization method. To verify the effectiveness, the proposed method was applied to in situ TRTs, and the results were compared with those from the conventional method with regard to the estimation stability and convergence speed. The objectives for the development of the new estimation method were strong robustness, fast convergence, and low computation costs for a wide practical applicability.

The second half of this thesis concerns the effect of natural convection in a saturated porous formation on the TRT results. First, to examine the performance dependence of a BHE installed in a saturated porous formation on the heat injection rate, TRTs were conducted in two BHEs having the same geometry but different backfill materials: one was cement-grouted, and the other was gravel-backfilled. TRTs were conducted for each BHE at two different single-heat injection rates (approximately 40 and 80 W/m). The TRT data were analyzed with the developed estimation method. Based on the results, discussions are presented on existing design methods related to typical practices in TRTs and the advantages of backfilled BHEs from the perspectives of performance and constructability.

Lastly, new practical TRT and interpretation methods are suggested to overcome the temporal changes in the ground conditions when examining the heat rate dependence of the TRT results. The proposed TRT method uses multiple heat injection rates. The developed parameter estimation method using the ILS model and quasi-Newton method was corrected to successfully handle multi-heat injection rate TRTs. The effectiveness of the proposed method was verified using numerically generated multi-heat injection rate

TRT data. Four TRTs were conducted with two different BHEs installed in a saturated sandy formation. Because the estimation method was sufficiently fast and robust, a real-time estimation method for onsite TRTs is also proposed to reduce the test time.

In summary, this thesis examines the experimental disturbances to a TRT and the heat rate dependence of the TRT results caused by natural convection in the ground with the ultimate objective of improving the accuracy of BHE designs. Through theoretical, numerical, and experimental examinations and verifications, insights into TRTs were generated. The obtained theoretical and numerical results will be helpful to experimenters and can be used to elaborate upon existing guidelines. Alternative interpretation methods are proposed to consider the disturbance effect and examine the heat rate dependence in a saturated porous formation. The suggested interpretation method is computationally fast and robust. Therefore, it is expected to be of practical use for in situ TRTs. The use of the proposed methods will improve the accuracy of BHE designs.