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Tuning the performance of a borehole heat exchanger array in response to transient hydrogeological conditions

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Most shallow geothermal systems harness renewable energy from the ground by circulating a heat-carrier fluid through borehole heat exchangers (BHEs). While these systems have emerged as promising contributors to the ongoing energy transition, open questions regarding their durability and performance in practical applications remain. Critical factors are the uncertainty in the long-term heating/cooling demand as well as the uncertainty in the evolution of the ground thermal conditions. To enhance the environmental and economic appeal of such systems that should be operated for decades, optimal control procedures that adjust the heat extraction during the course of operation have been proposed. In this study, we introduce an improved sequential simulation-optimization procedure to tune the efficiency of BHEs exposed to transient groundwater flow conditions. The variability of groundwater flow not only perturbs subsurface heat transfer but also impairs the predictability through standard BHE modeling tools. For example, the well-established moving finite line source (MFLS) formulation offers no capabilities to represent transient trends in advective heat transport associated with groundwater flow. We restructure the MFLS by a time-varying groundwater flow term that ensures compliance with thermal equilibrium assumptions. This modified variant is validated with a numerical model and then interfaced with a linear programming algorithm to optimize the operation of the BHE array. To examine the efficacy of the proposed procedure, a synthetic field containing ten BHEs operating in the heating mode is implemented. Three distinct groundwater fluctuation scenarios, with monthly resolutions over a ten-year operational lifespan, are considered. The groundwater flow dynamic exhibits variations in an increasing, decreasing, and periodic manner. As the objective, local cooling is to be minimized. This is achieved by determining the monthly optimal load pattern for individual BHEs. The proposed methodology employs a cost function to minimize the maximum temperature change over two distinct temporal terms. The first term considers the entire operational lifetime, while the second term focuses on a forthcoming 12-month horizon.
The proposed methodology does not only achieve optimal BHE operation, but it also facilitates calibrating unknown or transient model parameters. This is demonstrated for the groundwater flow velocity that is estimated by solving a nonlinear least-squares problem using the trust-region-reflective algorithm. The benefit of sequential learning is compared with results obtained by optimization without any model calibration. This calibration-optimization routine, informed by transient temperature changes in the simulated ground, outperforms sequential optimization that relies on non-tunable model parameters.