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Near-surface geothermal energy

Shallow Geothermal Energy Utilization in Alluvial Aquifers: Insights from Thermal Response Testing and Monitoring in a Commercial Building in Zagreb, Croatia

Nutzung von oberflächennaher geothermischer Energie in alluvialen Grundwasserleitern: Erkenntnisse aus thermischen Reaktionstests und Überwachungen in einem Geschäftsgebäude in Zagreb, Kroatien

Tomislav Kurevija, Maria Macenić, Luka Perković, Kristijan Posavec, Marko Sinčić

University of Zagreb – Faculty of Mining, Geology and Petroleum Engineering

Shallow geothermal energy systems utilizing borehole heat exchangers (BHEs) represent a important sustainable heating and cooling solutions today, particularly in urban environments where space constraints and environmental regulations demand efficient, low-carbon alternatives to traditional fossil fuel-based systems. The efficiancy of such systems is heavily influenced by local geological, thermogeological and hydrogeological conditions. In regions with high groundwater hydraulic conductivity, such as alluvial aquifers, convective heat transfer can significantly enhance heat extraction and rejection rates of the BHE. This study presents empirical findings from the installation and monitoring of a ground source heat pump (GSHP) system in a commercial building in Velika Gorica, near Zagreb, Croatia. The system comprises eight vertical BHEs, each 100 meters deep, embedded within a Quaternary alluvial aquifer characterized by substantial groundwater flow. A thermal response step test (TRST) conducted on the site revealed a high effective thermal conductivity coefficient, attributable to positive convective heat transfer driven by groundwater advection. This configuration serves as a testbed for evaluating thermo-hydro-mechanical (THM) interactions in convective-dominated regimes, contributing to broader research objectives under the InnoGeoPot project (Innovative Research Methods for Assessing Geothermal Energy and Thermal Energy Storage Potential), funded by the Croatian Science Foundation (IP-2022-10-4206).

The geological setting of the study site is near the river Sava alluvial plain which forms Zagreb shallow aquifer system. The area is dominated by Holocene and Pleistocene deposits, including gravels, sands, and silts, with thicknesses varying from 20 to 100 meters on a broader area. The aquifer is divided into two hydraulically connected layers: a shallow alluvial horizon (primarily coarse gravels and sands, up to 40 meters thick in the eastern parts) and a deeper marsh horizon (sands, gravels, and silty clays, up to 60 meters thick). The overburden, consisting of low-permeability clays, is minimal—typically 1 to 5 meters—allowing direct recharge from the Sava River and resulting in groundwater levels fluctuating during high and low river stages. Hydraulic conductivity in the upper aquifer reaches approximately 1 cm/s, while the lower layer exhibits values around 0.4 cm/s, both indicative of high permeability that facilitates significant groundwater flow. This flow regime introduces advective heat transport, which overlays conductive heat transfer, thereby amplifying the thermal performance of BHEs. Regional geothermal gradients in the area range from 4 to 5 °C per 100 meters, with static ground temperatures around 13,7 °C at the site, as measured during initial circulation prior to TRST.

The BHE installation involved drilling eight boreholes to 100 meters depth, each with a diameter of 152 mm, using specialized equipment. The heat exchangers consist of four 32 mm PE100 RC SDR11 pipes configured in a 2U-loop, grouted with a flexible mixture of 60% bentonite clay and 40% portland cement, achieving a thermal conductivity of 1.2 W/m·°C.. The TRT was performed on the first BHE (BHE-1) from 31st of July to 5th of August 2026, using a custom apparatus with a maximum heater capacity of 9.0 kW. Data logging employed a HOBO U30 Series Data Logger with HOBOware Pro Software, recording parameters at 5-minute intervals, including inlet/outlet temperatures, flow rates, voltage, current, and ambient conditions. The TRT methodology followed established protocols (Eskilson, 1987; Eklof & Gehlin, 1996, Kurevija 2018) to determine effective thermal conductivity, borehole thermal resistance and steady state extraction rates. The test then proceeded in three stepped power phases to simulate varying thermal loads and identify steady-state conditions.

First phase had duration of 70 hours with heaters operated at an average power of 6088 W, injecting 298 kWh into the ground. Inlet/outlet temperatures stabilized at +24.4/+26.9 °C, a 10.7 °C rise above static conditions, indicating robust heat extraction potential without significant subcooling. Second phase had duration of 24 hours with heaters operated at an average power of 4293 W, injecting 141 kWh into the ground. Inlet/outlet temperatures stabilized at +22.2/+24.1 °C and 8.4 °C above static. Third phase had duration of 24 hours with heaters operated at an average power of 2321 W, injecting 56 kWh into the ground. Inlet/outlet temperatures stabilized at +20.2/+19.2 °C and 5.5 °C above static. Analysis focused on the linear portion of the mean fluid temperature versus natural logarithm of time plot, post-15 hours to account for initial transient effects and borehole resistance. Analysis shows extremely high value of 3,16 W/m °C, significantly exceeding typical conductive-only scenarios (e.g., 1.5-1.8 W/m·°C for saturated sands/gravels due to—effects from convective enhancement of groundwater flow. Extraction capacity of the BHE, according to EN14511 norm (minimum allowable entering source temperature from BHE = 0°C) was determined to be 69,8 W/m, or 7 kW per one borehole, which is by far greatest extraction rate of BHE measured so far in Republic of Croatia.

These results underscore the advantages of alluvial aquifers for geothermal applications and BHE: advection mitigates long-term ground subcooling, promoting seasonal regeneration and sustained system efficiency. In non-permeable formations, conductive heat transfer alone leads to progressive temperature depletion over years, potentially degrading GSHP coefficient of performance (COP) and seasonal performance factor (SPF). Here, hydraulic gradients ensure thermal recharge, maintaining near-initial conditions annually.

This fieldwork monitoring integrates into the InnoGeoPot project, a trilateral collaboration between Croatia, Slovenia, and Switzerland aimed at advancing geothermal potential assessment and subsurface energy storage). Project InnoGeoPot focuses on developing multi-scale 3D geological, hydrogeological, and THM models for pilot areas, including urban Zagreb and Ljubljana, and transboundary aquifers in northwestern Croatia/northeastern Slovenia. The project addresses gaps in decision-support systems (DSS) for shallow-to-medium-deep BHEs (up to 500 m), incorporating parameters like thermal conductivity, diffusivity, hydraulic conductivity, and groundwater flow regimes. In Zagreb, where shallow aquifers exhibit high permeability but limited storage potential due to unconfined flow, the project also explores medium-deep options, potentially revitalizing abandoned hydrocarbon wells via coaxial retrofits for direct heat production or closed-loop circulation. Monitoring equipment installed at the site—including temperature sensors along BHE profiles, existing piezometers for hydraulic gradients, and energy and temperature meters in building and in heat pump—facilitates real-time data collection on THM interactions. This enables long-term validation of models, quantifying convective contributions and optimizing BHE spacing to minimize thermal interference in urban settings. Preliminary data from the site highlight a 20-30% efficiency gain from advection, informing DSS tools for site-specific designs.

The innovative aspects of this research lie in bridging field measurements with regional modeling: traditional TRT assumes conduction dominance, but here adaption of the protocols for convective regimes for enhanced accuracy were made. Using this recorded data at the site, future work under InnoGeoPot will expand to numerical simulations (e.g., using FEFLOW) for scenario forecasting, including climate change effects on groundwater levels and thermal plumes. Empirical insights from this site will calibrate these models, fostering sustainable geothermal deployment and policy tools for urban planners. In conclusion, this study demonstrates the transformative potential of convective-enhanced geothermal systems in alluvial aquifers, with the test site installation serving as a scalable prototype. By yielding high extraction rates and resilient performance, it advances low-carbon building solutions, while InnoGeoPot's interdisciplinary framework ensures transferable methodologies for global usage.

Ackknowledgment

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