Title Holistic Simulation of Heat Extraction Sheet Pile Walls for Renewable Energy Extraction

Saeed Tourchi[1], Arash Alimardani Lavasan[1], Carol Youssef Namnoum[2] and Pierre Hubsch[2]

[1]Research Group Computational Soil Mechanics and Foundation Engineering (COMPSOIL), Department of Engineering, Faculty of Science, Technology and Medicine, University of Luxembourg, Luxembourg

[2]ArcelorMittal Global Research and Development,, ArcelorMittal, Luxembourg

Abstract This study numerically investigates Heat Extraction Sheet Pile Walls (HESPWs) for low-temperature geothermal energy using a 3D transient heat-transfer model in COMSOL Multiphysics. We analyze how flow rates, boundary conditions, and thermal interactions between sheet piles, soil, canals, and the atmosphere affect performance in an urban canal context. Simulations show higher flow rates lower outlet temperatures but boost total heat extraction, while the Thermal to Pumping Power Ratio (TPR) drops due to increased pumping needs. Lower flow rates improve TPR but limit energy output. These trade-offs emphasize tailoring flow rates to goals—maximizing power for district heating or efficiency for smaller systems. HESPWs prove viable for urban infrastructure, combining structural support with sustainable heating and cooling.

Keywords: Geothermal energy, Heat Extraction Sheet Pile Walls, Heat transfer, Pumping power ratio.

1 Introduction

Global efforts to curb greenhouse gas emissions and reduce fossil fuel dependence have intensified the search for renewable heating and cooling solutions. The Intergovernmental Panel on Climate Change's call to limit warming to 1.5°C has driven governments toward clean energy, with the European Green Deal pushing for decarbonized buildings via geo-energy systems like geothermal structures (Laloui, Nuth, and Vulliet 2006; McCartney et al. 2019), nuclear waste repositories (Tourchi et al. 2021; Bumbieler et al. 2021; Tourchi et al. 2023), and soil-atmosphere interactions (Cui 2022; Jabbarzadeh et al. 2024; Scaringi and Loche 2022), including ground source heat pumps (GSHPs) and aquathermal technologies. GSHPs tap into the stable thermal reservoir of soil and groundwater, offering higher efficiency than air-source systems due to consistent subsurface temperatures.

Direct geothermal capacity has surged over two decades, underscoring shallow geothermal's role in climate goals (Ziegler and Koppmann 2019; Lund, Freeston, and Boyd 2011). To cut drilling costs and boost heat transfer, heat-exchange loops are integrated into structural elements like energy piles, diaphragm walls, tunnel linings, and heat extraction sheet pile walls, which double as structural supports and heat exchangers (Brandl 2006; Brandl 2010; Franzius and Pralle 2011; Schneider and Moormann 2010).

HESPWs, originally retaining structures for quay walls or excavations, can be retrofitted with fluid-carrying loops to exchange heat with adjacent water or soil. This dual-purpose design suits dense urban areas, eliminating new drilling needs, with studies showing HESPWs can manage hundreds of watts per meter (BV 2020; Ziegler and Koppmann 2019). While energy piles lead in adoption, planar systems like basement walls and tunnel linings show similar potential, with research on "thermo-active seal panels" offering strategies—optimizing groundwater contact, pipe placement, and flow rates—applicable to HESPWs. Lab and numerical studies confirm steel HESPWs leverage high thermal conductivity for heat exchange, potentially exceeding 400 W/m with water flow, though this requires thermomechanical analysis and corrosion protection. Urban canal upgrades are prime candidates for "energy quay" walls, aligning outputs with nearby building demands (Ziegler and Koppmann 2019). Planar energy geostructures like HESPWs provide cost-effective, space-saving alternatives to boreholes, optimized through integrated geotechnical, hydraulic, and thermal design.

2 Numerical Modeling

Numerical simulations of the HESPW system were conducted using COMSOL Multiphysics, integrating Heat Transfer in Solids and Heat Transfer in Pipes modules in a transient 3D model. The model evaluates heat extraction efficiency influenced by pipe flow rates, soil thermal conductivity, and external conditions, capturing conduction in soil and sheet pile, and convection within geothermal pipes. The 24 m U-shaped pipe (36 mm diameter) embedded within the steel sheet pile form a closed-loop system, modeled with laminar flow and dynamically computed heat transfer coefficients for accurate convective heat exchange. The steel sheet pile is modeled as a vertical structural element driven 14 m into the ground.

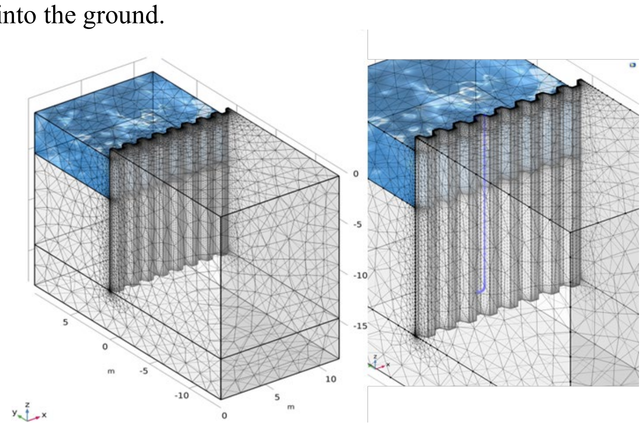
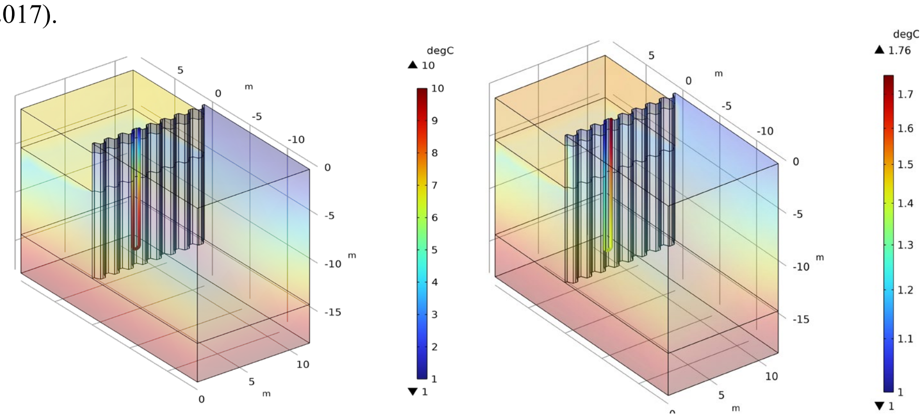


Fig 1. Geometric configuration of the ESPW model in COMSOL Multiphysics.

The initial temperature distribution in the soil and canal water domains is a key factor, setting the baseline thermal state for heat extraction with HESPWs. Rather than a uniform temperature, a depth-dependent interpolation function models subsurface temperature variations, reflecting geothermal gradients and seasonal shifts (**Fig 2a**). This ensures a realistic increase in temperature with depth, mimicking natural geothermal trends in the soil. In this study, the canal water temperature is set at a constant 7°C, despite a 1°C ambient air temperature. This aligns with urban water bodies' thermal behavior, where thermal inertia, groundwater inflow, urban heat retention, and anthropogenic effects often keep water warmer than surrounding air, especially in winter (Van Megchelen, 2017).



(a) (b)

Fig 2. (a) Initial temperature boundary conditions; (b) 3D temperature distribution of the HESPW system after 1 day of operation, simulated with a volumetric flow rate of 1.528 × 10−4 m3/s.

The geothermal pipes' inlet temperature, set at a constant 1°C, drives the thermal gradient for heat extraction, reflecting peak winter conditions after fluid passes through a heat pump or exchanger. The volumetric flow rate significantly influences heat exchange in thermo-active geostructures like HESPWs. Higher flow rates reduce the fluid's residence time in embedded pipes, decreasing the temperature difference between inlet and outlet, yet the increased fluid volume per unit time often enhances total heat extraction up to practical limits. Optimizing energy yield and pumping demands requires balancing these opposing effects. This study examines six flow scenarios (Fig 2b; Fig 3) to assess how flow magnitude impacts HESPW thermal performance. This range covers low laminar flow to higher velocities nearing the transition regime, reflecting typical operational conditions for energy geotechnical systems where turbulent flows are avoided due to excessive pumping costs, especially in building-scale applications.

3 Results and Discussion

Numerical simulations explored how volumetric flow rates affect heat extraction in a Heat Extraction Sheet Pile Wall (HESPW) system, using a 24 m U-shaped pipe (36 mm diameter) embedded in the wall. Fig 3 shows outlet fluid temperatures for six flow rates (0.028 L/s to 0.1528 L/s) over 1 day, with a constant inlet temperature of 1.0 °C. Results indicate lower flow rates (e.g., 0.028 L/s) produce higher outlet temperatures (~3.05 °C), while higher rates (e.g., 0.1528 L/s) yield lower temperatures (~1.75 °C).

This highlights a key trade-off: low flows allow more heat absorption due to longer residence time, increasing the temperature difference, whereas high flows limit temperature rise but boost total heat extraction power ($Q_v \times \Delta T$) due to greater fluid volume.

Comparing the scenarios shows that higher flow rates reduce outlet temperatures but may increase total heat extraction. Optimal flow balances pumping costs and efficiency, with the transition regime (2,300 < R_e < 10,000) enhancing heat transfer without excessive friction. Even small flow adjustments measurably impact outlet temperature and HESPW thermal performance.

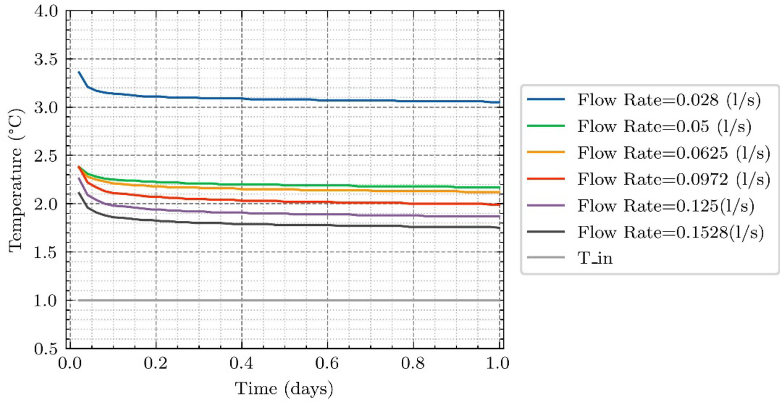


Fig 3: Temperature evolution over a 24-hour period for various flow rates in geothermal pipes.

4 Thermal Performance and Efficiency Analysis

Total heat extraction, denoted as P, represents the volumetric heat capacity of water, Q_v is the volumetric flow rate (m^3/s), and T_{out} and T_{in} are the outlet and inlet temperatures, respectively. Specific power, defined as normalizes the total heat extraction by the pipe length. Simulations conducted over a 24-hour period with a constant inlet temperature evaluated the heat extraction performance across six distinct flow rates, with results summarized in Table 1.

Table 1. Heat Extraction, Specific Power, Pumping Power and TPR at Different Flow Rates.

Flow Rate (L/s)	T_{out} (°C)	ΔT(K)	P(W)	P_{spec} (W/m)	P_{pump} (W)	TPR
0.028	3.05	2.05	241	10.0	0.0006	373,000
0.050	2.17	1.17	246	10.3	0.0020	119,417
0.0625	2.12	1.12	294	12.3	0.0054	53,747
0.0972	1.99	0.99	404	16.8	0.0186	21,720
0.125	1.87	0.87	457	19.0	0.0367	12,452
0.1528	1.75	0.75	482	20.1	0.0640	7,531

As the flow rate increases, the total heat extraction rises from 241 W to 482 W, while the temperature difference decreases from 2.05 K to 0.75 K . This trend indicates that higher flow rates circulate more fluid, enhancing overall heat transfer despite shorter residence times in the pipe. The specific power also increases from 10.0 W/m to 20.1 W/m, demonstrating improved heat extraction efficiency per meter of pipe. The system's efficiency is evaluated using the Thermal to Pumping Power Ratio (TPR), defined as $\mathrm{TPR} = \mathrm{P}_{\mathrm{thermal}} / \mathrm{P}_{\mathrm{pump}}$, where $P_{\mathrm{thermal}} = P$ (from Table 1), and P_{pump} is the power required to circulate the fluid. The pumping power is calculated dynamically using the Darcy-Weisbach equation for pressure drop (ΔP) and the relationship $P_{pump} = Q_v \cdot \Delta P$, with the friction factor determined by the flow regime via the Reynolds number. The TPR decreases significantly from 373,000 at $0.028\ \mathrm{L/s}$ to 7,531 at $0.1528\ \mathrm{L/s}$. This decline occurs because P_{pump} increases more rapidly than P_{thermal} with higher flow rates, highlighting a trade-off: greater heat extraction comes at the cost of reduced efficiency due to higher energy demands for pumping.

Optimizing the flow rate in the HESP system balances maximizing heat extraction with energy efficiency. The trade-offs among thermal power output, temperature difference, and pumping power across tested flow rates highlight the importance of selecting conditions tailored to specific applications. The simulations indicate high theoretical efficiency due to very low pumping power requirements. However, the practical choice of flow rate significantly affects the system's heat extraction capacity and compatibility with downstream equipment, such as heat pumps. The highest flow rate (0.1528 L/s) maximizes thermal output and is ideal for high thermal demand scenarios. Conversely, the lowest flow maximizes efficiency, ideal for heat pumps requiring larger temperature gradients. Intermediate flow rates provide a practical compromise between high thermal output and efficiency, accommodating common equipment specifications and energy budgets. The sharp decline in TPR with increasing flow rate results from a nonlinear rise in pumping power, typically proportional to the cube of flow rate (Q^3). Real-world factors may significantly alter these results, emphasizing the importance of realistic modeling.

5 Conclusions

This study demonstrates that HESPWs effectively harness shallow geothermal energy while providing structural support, offering a dual-function solution ideal for urban canal environments. Using a 3D coupled heat-transfer model in COMSOL, we evaluated how flow rate, inlet temperature, and boundary conditions influence heat extraction and thermal-to-pumping power ratios. Results indicate that higher flow rates increase thermal output but reduce temperature gradients, requiring an operational balance to optimize performance and efficiency. Site-specific factors—including soil thermal properties, groundwater flow, and realistic pumping requirements—further impact these trade-offs and should inform future analyses. Practical implementation of HESPWs must address geotechnical constraints, corrosion protection, and local hydrogeological conditions. Empirical validation and in-situ monitoring remain essential for confirming simulations and refining system designs. The integrated modeling approach presented here enhances engineering decisions, highlighting HESPWs as a sustainable solution for renewable heating and cooling in densely populated areas.

Acknowledgements The authors gratefully acknowledges the financial support provided by the Luxembourg National Research Fund (FNR) under the project *EnergWALL – Energy Sheet Pile Walls for Underground Thermal Energy Storage*.

References

Brandl, H. 2006. “Energy foundations and other thermo-active ground structures.” Géotechnique 56:81–122.

Brandl, H. 2010. “Energy piles and diaphragm walls for heat transfer from and into the ground.” Proceedings of the Institution of Civil Engineers – Geotechnical Engineering 163:147–154.

Bumbieler, F., C. Plua`, S. Tourchi, M. N. Vu, J. Vaunat, A. Gens, and G. Armand. 2021. “Feasibility of constructing a full-scale radioactive high-level waste disposal cell and characterization of its thermo-hydro-mechanical behavior.” International Journal of Rock Mechanics and Mining Sciences 137:104555.

BV, CRUX Engineering. 2020. “Amsterdamse Kademuur als Energiefabriek.” Technical report.

Cui, Y. 2022. “Soil–atmosphere interaction in earth structures.” Journal of Rock Mechanics and Geotechnical Engineering 14:35–49.

Franzius, J.N. and N. Pralle. 2011. “Turning segmental tunnels into sources of renewable energy.” Proceedings of the Institution of Civil Engineers 164:35–40.

Jabbarzadeh, M., H. Sadeghi, S. Tourchi, and A. G. Darzi. 2024. “Thermo-hydraulic analysis of desiccation cracked soil strata considering ground temperature and moisture dynamics under the influence of soil-atmosphere interactions.” Geomechanics for Energy and the Environment 38:100558.

Laloui, L., M. Nuth, and L. Vulliet. 2006. “Experimental and numerical investigations of the behaviour of a heat exchanger pile.” International Journal for Numerical and Analytical Methods in Geomechanics 30:763–781.

Lund, J. W., D. H. Freeston, and T. L. Boyd. 2011. “Direct utilization of geothermal energy 2010 worldwide review.” Geothermics 40:159–180.

McCartney, J., N. Jafari, T. Hueckel, M. Sa´nchez, and F. Vahedifard. 2019. Emerging thermal issues in geotechnical engineering. Springer.

Scaringi, G. and M. Loche. 2022. “A thermo-hydro-mechanical approach to soil slope stability under climate change.” Geomorphology 401:108108.

Schneider, M. and C. Moormann. 2010. “GeoTU6—a geothermal research project for tunnels.” Tunnel 2:14–21.

Tourchi, S., M. A. Manica, A. Gens, J. Vaunat, M.-N. Vu, and G. Armand. 2023. “A thermomechanical model for argillaceous hard soils–weak rocks: application to THM simulation of deep excavations in claystone.” Ge´otechnique pp. 1–14.

Tourchi, S., J. Vaunat, A. Gens, F. Bumbieler, M. N. Vu, and G. Armand. 2021. “A full-scale in situ heating test in Callovo-Oxfordian claystone: observations, analysis and interpretation.” Computational Geotechnics 133:104045.

Van Megchelen, C. 2017. “Cool water effects on shallow surface water.” TU Delft Repository .

Ziegler, M. and D. Koppmann. 2019. “Energy sheet pile walls – Experimental and numerical investigation of innovative energy geostructures.” In Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering.