Effects of subzero temperature circulating fluids on the performance of Energy Micropiles

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Effects of subzero temperature circulating fluids on the performance of energy micro-piles

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Summary

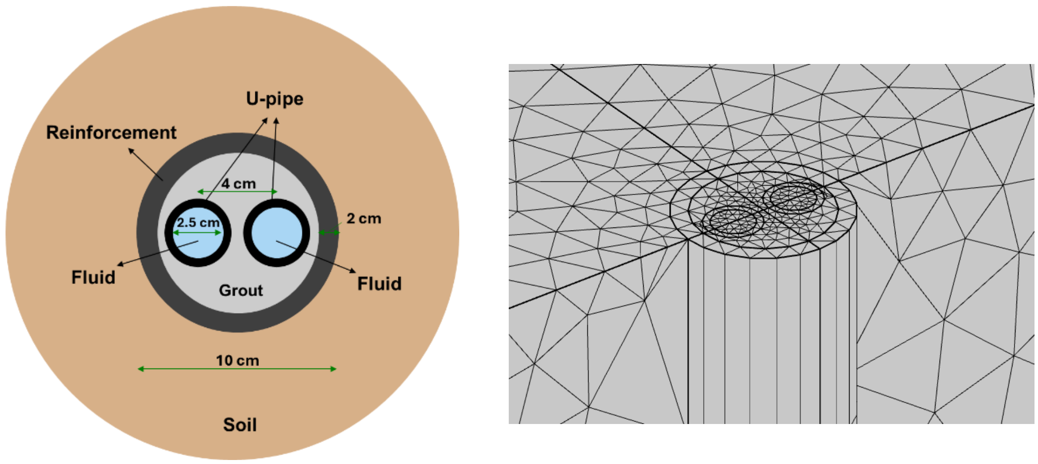
Micro-piles are Italian-patented small-diameter (typically < 300 mm) drilled and grouted piles reinforced with a steel tube. Recently, the integration of heat exchangers into micro-piles has led to the development of Energy Micro-Piles (EMPs), which serve the dual purpose of providing both structural support and thermal energy for heating and cooling. This innovative solution expands the utility of micro-piles, offering a promising approach for sustainable energy applications in civil engineering.
Maximising the temperature difference between the circulating fluid and the surrounding ground is crucial to optimise heat exchange. In winter, the fluid temperature of the heat exchangers can also drop below 0°C to enhance heat extraction. However, freezing of the soil at the EMP-soil interface must be avoided, as it may compromise foundation stability. For this reason, current guidelines conservatively recommend maintaining fluid temperatures above 0°C to prevent frost formation. In this study, a detailed three-dimensional thermo-hydraulic model of the EMP-soil system is developed to investigate heat transfer and potential soil freezing due to subzero fluid temperatures. Simulations across different soil types reveal that fine-grained soils are more prone to freezing due to their lower thermal diffusivity, which causes cold to accumulate and limits thermal power extraction – an effect that is less pronounced in coarse-grained soils.

1 Background

The Energy Micro-Pile (EMP) is an innovative extension of the traditional micro-pile, integrating heat exchanger pipes to combine structural support with geothermal energy use [1-4]. Their small size and versatility make them suitable for new and existing buildings. EMP performance depends on the temperature difference between the circulating fluid and the ground. While lower fluid temperatures in winter improve heat extraction, they may also induce soil freezing, which could compromise the structural efficiency of the foundation [5]. Current guidelines advise keeping fluid temperatures above 0 °C [6] and below 50 °C [7]. This study uses a three-dimensional (3D) thermo-hydraulic (TH) model to investigate the effects of subzero fluid temperatures on heat transfer and frost formation in various soil types.

2 Model

The model reproduces a detailed 3D geometry of the EMP-soil system, similar to what was developed by [2]. The cylindrical domain has a diameter of 2 m and a height of 21 m. It includes a 20 m-long energy micro-pile and a 1 m soil extension at the base to minimise boundary effects. Figure 1 shows a scheme of the cross section of the EMP characterised by an external diameter of 10 cm and consisting of an outer steel reinforcement tube, filled with a cementitious grout, and instrumented by a U-shaped polyethene tube functioning as a heat exchanger. The U-tube has an internal diameter of 2.5 cm and a wall thickness of 0.4 cm. It is filled within the cement grout, and a water–glycol mixture (25% glycol by volume) is the circulating heat carrier fluid. The two branches of the U-tube are spaced 4 cm apart (centre-to-centre).



(a) (b)

Fig. 1 – (a) scheme of the cross section of the EMP; (b) computing mesh detail

To simultaneously evaluate the field of temperature and frozen soil around the EMP, a coupled TH formulation solving thermal energy and water mass balance equations was implemented using COMSOL Multiphysics®. For details about the TH model and the additional constitutive relationships required, see [9].

3 Simulations

A sensitivity analysis was set up to explore different soil types and sub-zero temperatures of the circulating fluid. The relevant physical, thermal, and hydraulic properties adopted for soil types like sand, silt and clay are summarised in Table 1. Physical and thermal properties are related to those of solid grains. The overall soil properties are obtained by combining the properties of the constituent phases as indicated in [9].

Table 1: Soil physical, thermal, and hydraulic properties.

	Physical properties		Thermal properties		Hydraulic properties			
Soil	ρ	ϕ	c_p	λ	S_{res}	m	IEV	K_{sat}
	$[kg/m^3]$	$[-]$	$[J/(kg \cdot K)]$	$[W/(m \cdot K)]$	$[-]$	$[-]$	$[kPa]$	$[m/s]$
Sand	2700	0.45	800	4	0.04	0.8	4	10^{-4}
Silt	2650	0.40	900	2	0.08	0.5	70	10^{-6}
Clay	2600	0.35	1000	1.5	0.20	0.3	200	10^{-8}

A time-dependent temperature profile is set as a boundary condition according to Hillel's model [8], assuming an undisturbed temperature of 13.5°C, and a mean annual and diurnal surface temperature range of 16°C and 3.5°C, respectively. The top of the micropile is assumed to be thermally insulated. The pore water remains constant in space and time, with the initial value p_{w0}=0 Pa. The circulating heat carrier fluid has a prescribed velocity of 1.7 m/s, corresponding to a turbulent flow, which enhances the heat exchange. The prescribed inlet temperatures of the circulating fluid investigated in this work are –5°C and –10°C.

4 Results

Temperature profiles were analysed at the pile–soil interface, where freezing and thawing processes may alter soil properties and affect the load-bearing capacity of the pile. Figure 2(a) presents temperature profiles along the soil-pile interface closest to the inlet pipe (point A in Figure 2) for different soil types, with a given inlet fluid temperature of $T_{in} = -5$°C after 7 simulation days. Due to its low thermal diffusivity, clay tends to exhibit the lowest temperatures, as it inhibits heat transmission and leads to more localised thermal gradients. In contrast, sand, characterised by higher thermal diffusivity, shows freezing phenomena only in limited sections along its depth, remaining unfrozen elsewhere. Silt displays intermediate behaviour between the two.

Figure 2 (b-c) shows contours of the ice saturation degree, S_i, defined as the ratio between the volume of ice and the total pore volume, for the different soil types and the fluid inlet temperatures (T_{in}). At $T_{in} = -5$°C and a depth of $z = -2$ m, silt and clay reach a frozen soil thickness of approximately 40 mm, considering S_i>0.2 as the threshold, whereas sand reaches only 9 mm, confined to a narrow vertical region and remaining unfrozen elsewhere. As expected, the frozen soil thickness increases with decreasing inlet fluid temperature, due to the stronger thermal gradients.

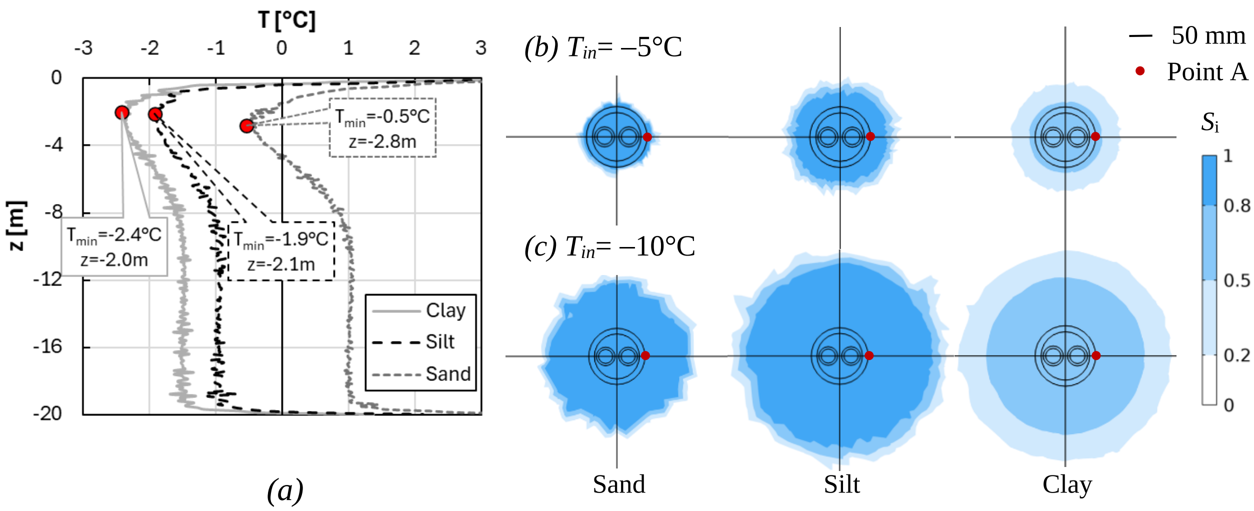


Fig.2 – (a) Temperature profiles at the micropile–soil interface; contours of the ice saturation degree for the three different soils at (b) T_{in}=-5°C (c) T_{in}=-10°C.

5 Thermal power

The thermal power produced by the EMP–soil system, representing the usable energy for heat pump operation, is calculated per unit length (L_p [m]) based on the temperature difference between the inlet and outlet of the heat carrier fluid:

$$q = \dot{m} c_p \Delta T / L_p \tag{4}$$

where q is the thermal power [W/m], $\dot{m}$ is the fluid mass rate [kg/s], c_p, is the fluid specific heat capacity [J/(kg·K)], and ΔT is the inlet–outlet temperature difference [°C]. The mass rate is defined as $\dot{m} = \rho_f(T) u \pi r^2$, where $u = 1.7$ m/s is the fluid velocity, $r = 0.0125$ m is the radius of the pipe, and $\rho_f(T)$ is the temperature-dependent density of the water–glycol mixture [kg/m³]. For instance, at an inlet temperature $T_{in} = -10$°C, ρ_f=1032.5 kg/m³.

Figure 3 (a) shows the evolution of thermal power for $T_{in} = -10$°C in the three analysed soil types. In all cases, the thermal power decreases over time, attaining an asymptotic value, which is proportional to the soil thermal diffusivity, which also accounts for the presence of ice. In high thermal diffusivity soils such as sand, thermal power remains higher due to more efficient heat transfer, which helps maintain a larger temperature difference between T_{in} and T_{out}. Figure 3 (b) presents the thermal power output in sand for different inlet temperatures, confirming that lower T_{in} values lead to increased thermal energy exchange, consistent across all soil types.

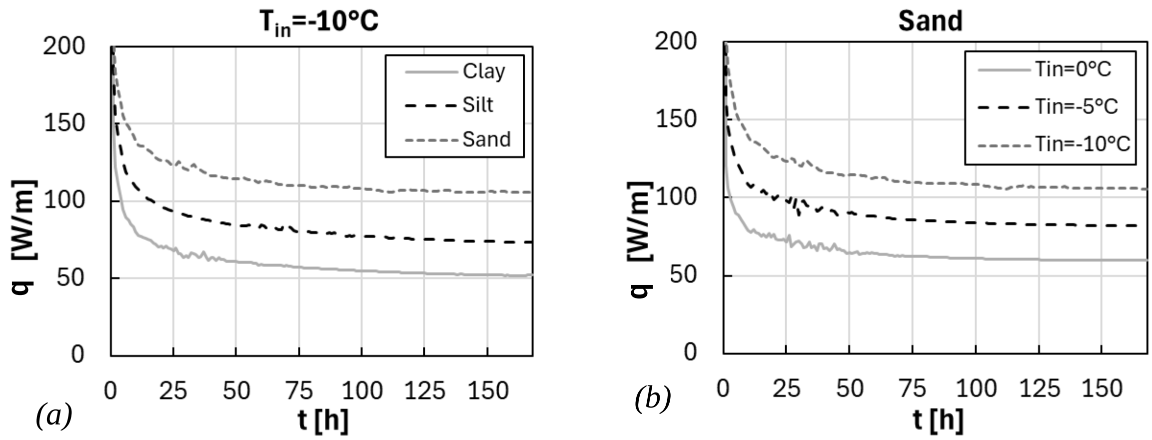


Fig.3 - Evolution of thermal power: (a) for different soil types at a given inlet temperature of the circulation fluid (b) for varying circulating fluid inlet temperatures in sand.

6 Conclusion

In this work, the effect of subzero fluid temperatures on the energy performance of an EMP was investigated via numerical modelling. With an inlet temperature of −10°C, all soil types experienced a significant freezing. At -5 °C, silt and clay froze, while sand exhibits a localised freezing around −2 m depth. Fine-grained soils were more susceptible to freezing due to their lower thermal conductivity. Thermal power increased with decreasing fluid temperature and was higher in coarse-grained soils.

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