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1 **A numerical study into effects of soil compaction and**  
2 **heat storage on thermal performance of a Horizontal**  
3 **Ground Heat Exchanger**

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## Abstract

The good capacity of the numerical simulations makes possible to bring some further responses on the backfill soil selection and its installation depth in the Horizontal Ground Heat Exchanger (HGHE). Therefore, a well-known backfill soil was considered to be used as substitutive material. The hydrothermal properties of the backfill material were estimated in laboratory and then injected in a numerical framework considering the atmosphere-soil-HGHE interaction. Numerical simulations were performed for a HGHE installed in the compacted backfill soil and the local natural soil. The simulation results showed that the compacted backfill soil improves by 8.5% the HGHE performance compared to local uncompact soil. Two heat storage scenarios at three different installation depths were also investigated. The results showed that an inlet fluid temperature of 50 °C in summer increased highly the system performance by 13.7% to 41.4%, while the improvement was less significant (0% to 4.8%) for the ambient inlet temperature scenario. A deeper installation depth of HGHE increased also the system performance, the more energy could be stored and extracted.

**Keywords:** Horizontal Ground Heat Exchanger; Numerical simulations; Atmosphere-soil-HGHE interaction; Backfill soil; Installation depth; HGHE Performance.

# 1 Introduction

Shallow geothermal energy is one of the many sources of renewable energy, and it can be easily accessed all around the world (H Abedin and A Rosen 2011; Shortall et al. 2015; Sangi and Müller 2018). The temperature of the ground can be exploited during winter using a ground source heat pump for space heating and during summer for cooling needs. To increase the efficiency of shallow geothermal energy the solar energy can be stored during summer to increase the temperature of the ground (Xu et al. 2014; Lee et al. 2018; Lahoori, Jannot, Rosin-Paumier, Boukelia and Masrouri 2020). Generally, open and closed heat exchangers are available for the exploitation of shallow geothermal energy (Florides and Kalogirou 2007), which are then served as low-potential sources of thermal energy for heat pumps (Adamovsky et al. 2015). Horizontal Ground Heat Exchanger (HGHE) is one of those closed loop heat exchangers. Compared to Vertical Ground Heat Exchanger (VGHE), it is more cost effective although it requires more installation space (Self et al. 2013).

Due to the shallow installation depth (conventionally between 1.0 and 2.0 *m*), HGHE is also more sensitive to the meteorological condition (Gonzalez et al. 2012; Habibi and Hakkaki-Fard 2018). The experimental investigations showed that the thermal performance depends on the depth of HGHE installation (Beier and Holloway 2015). At deeper position, the soil thermal properties are not affected by the daily and seasonally ambient temperature variation. The results reported by Elminshawy et al. (2017) showed that the thermal performance of the horizontal system highly depends on the soil compaction state (water content and density) and air flow rate. By increasing density, the solid particles are better packed into a unit volume and the number of contact points between the particles increases (Penner et al. 1975; Abu-Hamdeh and Reeder 2000). These contact points provide a larger heat transfer by conduction which causes the temperature variation between the inlet and outlet airflow. These observations are in agreement with the study of Hurtado et al. (2012) which investigated the capacity of a compacted soil to store thermal energy from the chimney power plant using an analytical model based on a finite volume procedure. They mentioned that the output power energy was increased by 10%

64 when the soil compaction increased from loose to dense level.

65 Since the experimental investigations are time and money consuming, the thermal  
66 performance of horizontal heat exchanger loops in soils has been numerically investigated  
67 using finite element and finite difference tools in different studies. Normally in these  
68 models, the simulation is done by considering a homogeneous soil mass with constant  
69 thermal properties and the heat transfer is modeled by conduction using solid particles of  
70 soil (Jradi et al. 2017). However, in unsaturated compacted soils, the thermal properties  
71 will change by temperature variations, soil physical and hydraulic properties. Therefore,  
72 a comprehensive investigation is a thermo-hydraulic simulation with consideration of the  
73 mass transfer by vapor and liquid flows (Gan 2013; Gao et al. 2016; Boukelia 2016; Li  
74 et al. 2018; Li et al. 2018). Asgari et al. (2020) showed that the thermal performance  
75 of the linear and slinky types of HGHE increases by increasing the number of layers  
76 arrangement in the ground. For the spiral type exchangers, the thermal performance  
77 did not change with increasing the number of layers. Boukelia (2016) investigated the  
78 heat lost in a seasonal storage system in an embankment using HGHE by conducting the  
79 coupled thermo-hydraulic numerical simulations with a finite element tool (Code-Bright).  
80 The author observed that when the inlet temperature in the HGHE during summer was  
81  $50\text{ }^{\circ}\text{C}$ , the temperature of the soil close to the probes reached  $38\text{ }^{\circ}\text{C}$ . At the end of the  
82 autumn when the thermal extraction season started, the temperature was about  $25\text{ }^{\circ}\text{C}$ ,  
83 therefore, about  $13\text{ }^{\circ}\text{C}$  of heat loss has been occurred. Jradi et al. (2017) showed the  
84 efficiency of the Air Source Heat Pump (ASHP) combined with a solar power system as a  
85 basis for seasonal thermal energy storage. They showed also that a huge heat loss occurred  
86 after storage seasons. Therefore, to increase the thermal performance of a medium to store  
87 thermal energy, the insulation material covering the soil might be a good option and it  
88 can be taken into account in the design stage (Lahoori, Rosin-Paumier, Stoltz and Jannot  
89 2020).

90 Another challenging issue is the consideration of the atmosphere-soil-HGHE interac-  
91 tion in the prediction of the system performance. Tang and Nowamooz (2020) proposed  
92 a numerical simulation framework to evaluate the HGHE performance in field conditions

93 by considering energy and water balance on the land surface. They showed in their sim-  
94 ulations that the consideration of the atmosphere-soil-HGHE interaction underestimates  
95 highly the outlet temperature especially for the horizontal systems installed close to the  
96 soil surface up to a difference of 48%.

97 The good capacity of the numerical framework considering the atmosphere-soil-HGHE  
98 interaction makes possible to bring some further responses on the backfill soil character-  
99 istics and the installation depth rarely studied so far. This point is very crucial for the  
100 thermal performance of the horizontal systems. Modeling the soil characteristics such  
101 as the compaction state and thermal properties may significantly improve the system  
102 performance, and also avoid the cost of HGHE installation at deeper depths.

103 In this context, the investigation aims to visualize how the compacted backfill soil  
104 would influence the HGHE performance. In addition, two energy storage scenarios are  
105 compared at different installation depths, giving a highlight on how the installation depth  
106 would influence the energy storage applications in HGHE. Therefore, a compacted backfill  
107 soil which hydric and thermal properties have been measured in laboratory, is considered.  
108 Then, hydrothermal properties of the compacted soil are estimated and embedded in the  
109 numerical framework considering the atmosphere-soil-HGHE interaction.

## 110 **2 Hydrothermal behavior of the studied soil**

111 The studied soil is frequently used as the backfill soil in France. The material was  
112 classified as sandy lean clay, CL, according to the Unified Soil Classification System  
113 (ASTM 2000). Regarding the X-ray diffractograms analysis the compacted soil contains  
114 81% quartz, 7% dolomite, 5% calcite, 5% clayey materials and 3% feldspar. According to  
115 the particle-size distribution, almost 20% of the particles of the soil were smaller than 2  
116  $\mu m$  corresponding to the clay content, and 59% were higher than 0.05  $mm$  corresponding  
117 to the sand content ( $x_s$ ). With a liquid limit (LL) of 27% and a plastic limit (PL) of  
118 21%, the plasticity index (PI) was 6%. The backfill soil is compacted at a water content  
119 of 16.3% to reach a dry density of  $1.72 Mg.m^{-3}$  as a reference state.

120 Figure 1 shows the variation of the water content with the suction for the compacted  
 121 soil at its reference state. The van Genuchten equation (van Genuchten 1980) is used to  
 122 model the Soil Water Retention Curve (SWRC):

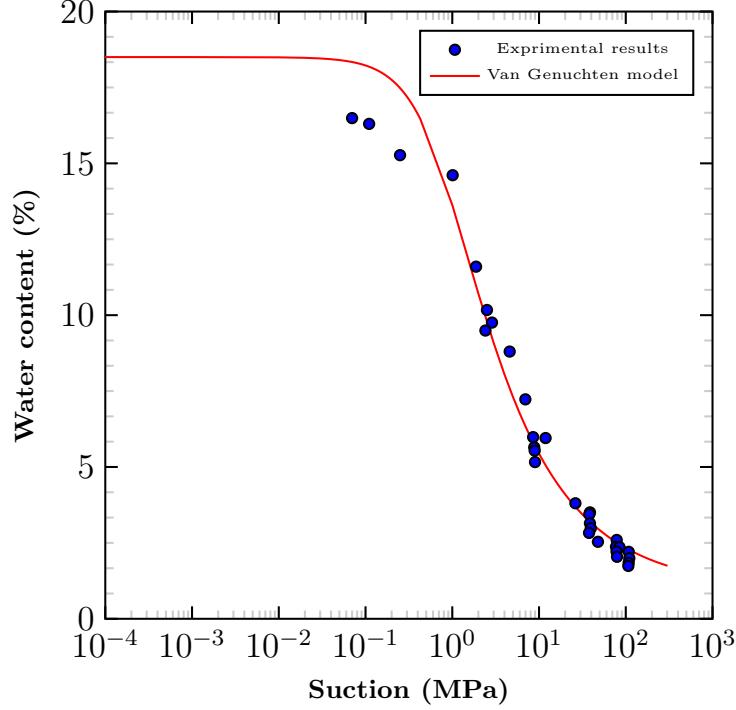


Figure 1: SWRC of the studied compacted backfill soil at reference compaction state ( $w=16.3\%$  and  $\rho_d=1.72 \text{ Mg.m}^{-3}$ )

$$w = w_r + \frac{w_{sat} - w_r}{(1 + (\alpha s)^n)^m} \quad (1)$$

123 where  $w$  is the soil water content at the suction  $s$ ;  $w_{sat}$  and  $w_r$  are the saturated water  
 124 content and the residual water content;  $\alpha$  is a parameter related to the air entry suction;  
 125  $m$  and  $n$  are the model constant parameters with  $m = 1 - 1/n$ . Table 1 summarizes the  
 126 main parameters of the SWRC used for the studied soil.

Table 1: Hydrothermal properties of the studied soil.

Application	$K(m.s^{-1})$	$l(-)$	$\alpha(m^{-1})$	$n(-)$	$w_r(-)$	$x_s(-)\%$	$\rho_s(Mg.m^{-3})$
Compacted backfill soil	$1.10^{-9}$	0.5	0.0134	1.52	0.01	0.62	2.60

127

128 Figure 2 shows the variation of the hydraulic conductivity of the studied material with

129 suction. The hydraulic conductivity was measured in saturated conditions with triaxial  
 130 device and in the unsaturated state with the Wind method (Wind 1966). A combined  
 131 equation of van Genuchten (1980) and Mualem (1976) is used to calculate hydraulic  
 132 conductivity with suction:

$$k = K(S_e)^l(1 - (1 - S_e^{1/m})^m)^2 \quad (2)$$

$$S_e = \frac{w - w_r}{w_{sat} - w_r} \quad (3)$$

133 where  $K$  is the saturated hydraulic conductivity ( $m.s^{-1}$ ),  $S_e$  is the relative saturation of  
 134 the soil and  $l$  is the pore connectivity parameter. These fitted parameters of Mualem-van  
 135 Genuchten equation are also summarized in Table 1.

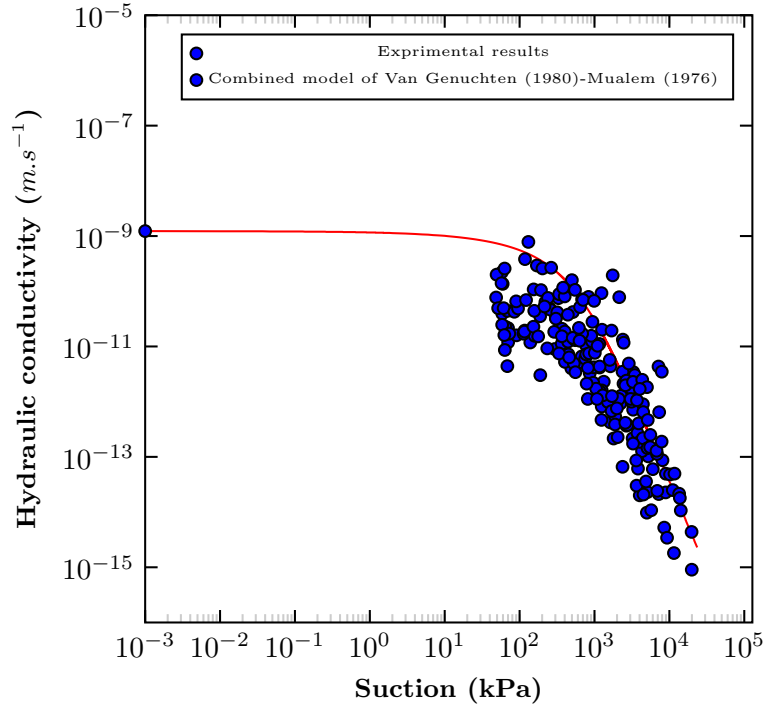


Figure 2: Hydraulic conductivity of the studied backfill soil.

136 The thermal properties were defined for the reference compaction state of the stud-  
 137 ied material. The thermal conductivity and volumetric heat capacity were measured by  
 138 KD2 Pro method (Devices et al. 2016). These values are  $2.46 W.m^{-1}.K^{-1}$  and  $3.25.10^6$   
 139  $J.m^{-3}.K^{-1}$  respectively.



140 The approach proposed by Nowamooz et al. (2015) and Nikoosokhan et al. (2015) is  
 141 used to model the soil thermal conductivity:

$$k_s = (0.443x_s + 0.081\gamma_d) \frac{(4.4x_s + 0.4)S_r}{1 + (4.4x_s - 0.6)S_r} + 0.087x_s + 0.019\gamma_d \quad (4)$$

142 where  $x_s$ ,  $\gamma_d$ , and  $S_r$  are the soil sand content, dry unit weight ( $kN.m^{-3}$ ) and degree  
 143 of saturation, respectively.

144 The approach proposed by Tang and Nowamooz (2018a) and Tang and Nowamooz  
 145 (2018b) is also used to calculate the soil volumetric heat capacity:

$$C_{v-s} = (4.18 - 0.095\gamma_d - 0.3x_s)S_r + 0.09\gamma_d - 0.2x_s \quad (5)$$

### 146 3 General conditions of the numerical simulations

147 General geotechnical, meteorological, hydrothermal and system conditions are given in  
 148 this section.

#### 149 3.1 Geotechnical conditions

150 The studied geometry has a length of 30  $m$ , a width of 12  $m$  and a height of 20  $m$ . This  
 151 deep geometry is selected to have no hydrothermal impact of the seasonal metrological  
 152 condition on the bottom boundary. A slinky-type HGHE with 0.03  $m$  of inner diameter  
 153 and 0.036  $m$  of outer diameter is installed 1  $m$  below surface, covered with the backfill  
 154 soil compacted at dry densities of 1.72  $Mg.m^{-3}$ .

155 We considered that the HGHE system and its backfill are installed in Alsace region in  
 156 France in June. The local natural soil surrounding the HGHE till 1  $m$  of depth (installation  
 157 depth) is completely replaced by the backfill soil (Figure 3). The local soil is mainly  
 158 constituted of sandy loam and its hydrothermal properties are listed in Table 2.

Table 2: Hydrothermal properties of the subsurface soils.

Application	$K(m.s^{-1})$	$l(-)$	$\alpha(m^{-1})$	$n(-)$	$w_s(-)$	$w_r(-)$	$x_s(-)$	$\rho_s(Mg.m^{-3})$	$\rho_d(Mg.m^{-3})$
Sandy loam	$1.78.10^{-5}$	0.5	2.60	1.52	0.39	0.02	0.80	2.62	1.60

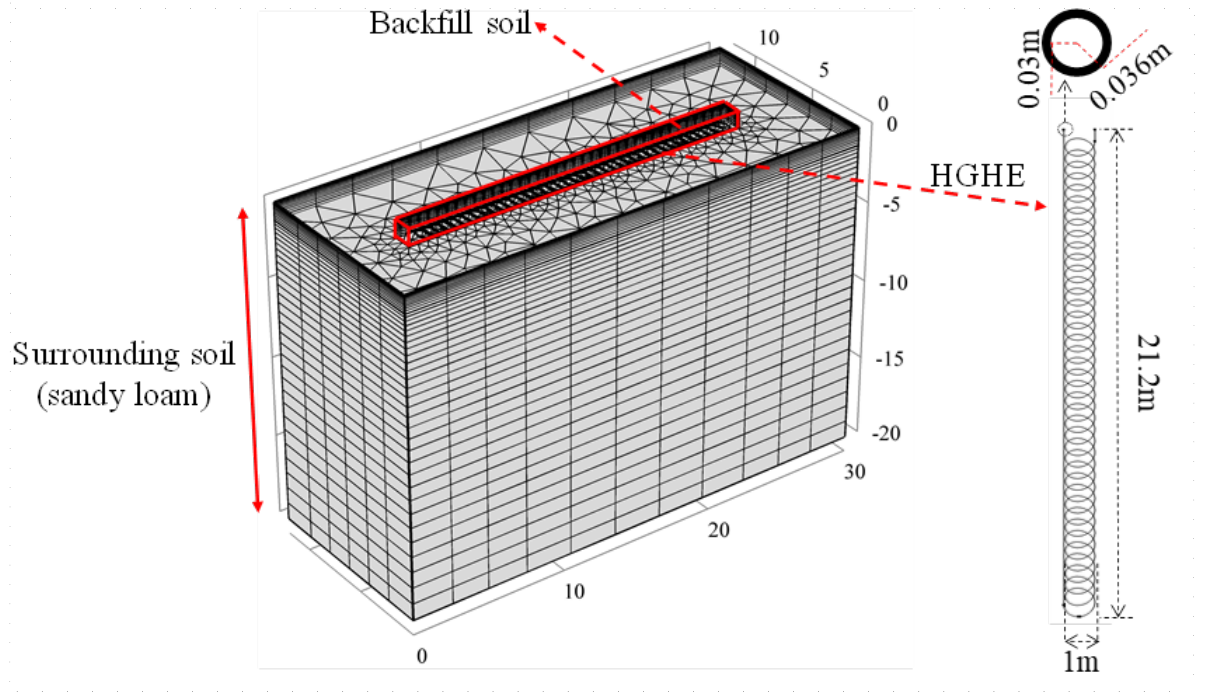


Figure 3: Geometry and its mesh for the numerical simulations.

159

160 A swept mesh is deployed to obtain reasonable computation time. It should be noted  
 161 that the generated meshes are denser in the shallow depths since the shallow ground is  
 162 more sensitive to hydrothermal fluctuation on the land surface. In addition, the meshes  
 163 around the HGHE are also denser due to the steep temperature and suction gradients  
 164 (Choi and Ooka 2016). The geometry and its mesh are shown in Figure 3.

### 165 3.2 Boundary and meteorological conditions

166 The temperature gradient at the bottom boundary is set  $0.142 \text{ K.m}^{-1}$  (Baillieux et al.  
 167 2013), and the extra water from the precipitation is drained at the bottom boundary. The  
 168 groundwater level is set constant at the depth of  $7.5 \text{ m}$  in the whole year. No hydrothermal  
 169 flow is imposed on the lateral boundaries.

170 The meteorological condition corresponds to the local condition with the installation  
 171 time in June (Tang and Nowamooz 2018b; Tang and Nowamooz 2019). The parameters  
 172 for the soil surface energy balance are reported in Table 5 in Appendix. Figure 4a and

173 Figure 4b present the ambient temperatures and the shortwave radiation for one year  
 174 represented by a simplified sinusoidal curve.

175 At the site, there is no obvious seasonal fluctuation of cloud cover, wind speed, precip-  
 176 itation and air humidity with time. Therefore, an average cloud cover of 0.41, an average  
 177 wind speed of  $2 \text{ m.s}^{-1}$ , an average monthly precipitation of  $55.7 \text{ mm}$ , and an average  
 178 air humidity of 83% are applied in the numerical simulation model to capture the main  
 179 meteorological condition of the local site.

180 For the surface water balance, 20% of precipitation run off, and the other 80% partic-  
 181 ipate into evapotranspiration or infiltration.

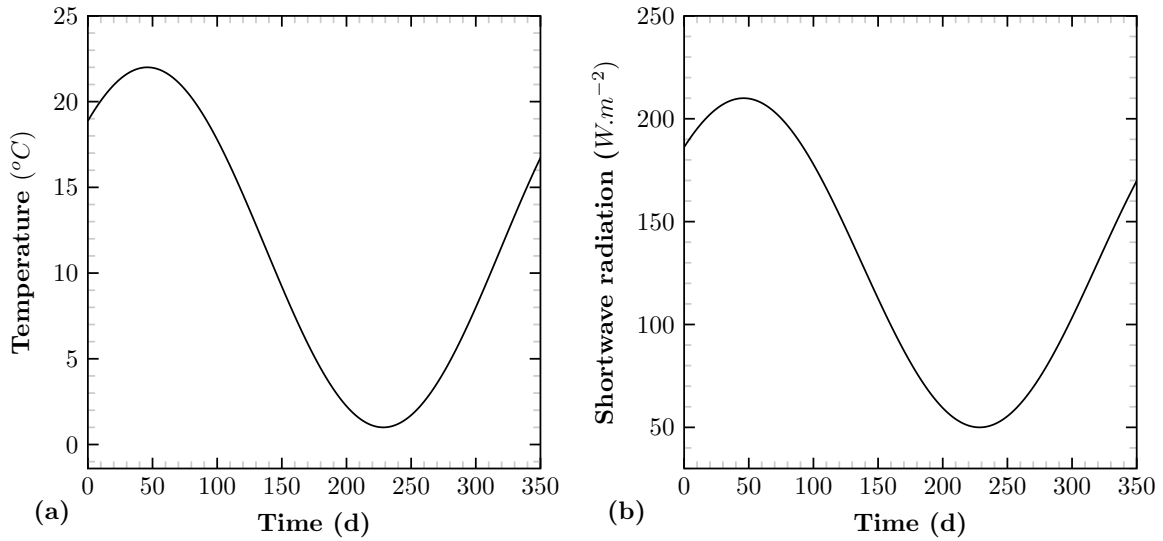


Figure 4: Simplified local meteorological condition: (a) ambient temperature fluctuation for one year and (b) shortwave radiation fluctuation for one year.

### 182 3.3 Initial hydrothermal conditions

183 An equilibrium method is used to obtain the initial hydrothermal profiles at its instal-  
 184 lation time in the end of summer. Figure 5 shows the suction and temperature profiles at  
 185 this time.

### 186 3.4 Pipe and its carrying fluid

187 The pipe is a High-Density Polyethylene Pipe (HDPE) with the thermal conductivity of  
 188  $0.4 \text{ W.m}^{-1}.K^{-1}$ . Propylene Glycol (PG) with a volume concentration of 25% is selected as

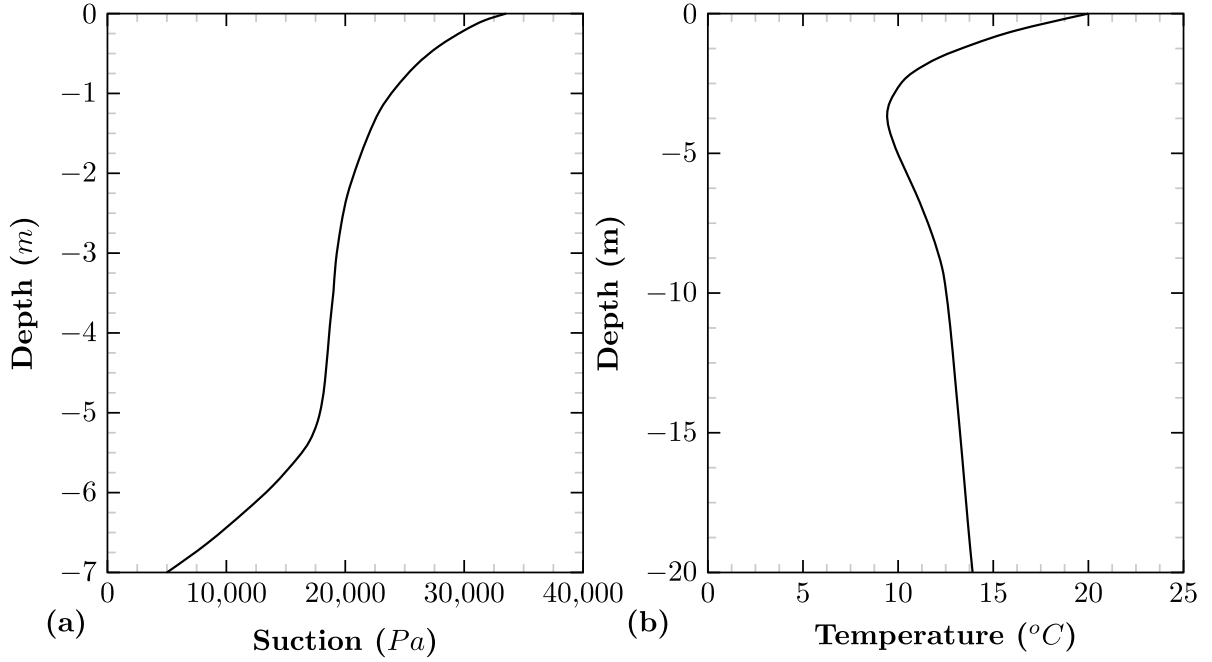


Figure 5: Initial hydrothermal profiles: (a) suction profile and (b) temperature profile.

189 the carrying fluid. It has a dynamic viscosity of  $0.0055 \text{ Pa}\cdot\text{s}$ , a density of  $1026 \text{ kg}\cdot\text{m}^{-3}$ , a  
 190 thermal conductivity of  $0.45 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  and a specific heat capacity of  $3974 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$   
 191 (Casasso and Sethi 2014). The carrying fluid velocity is  $0.5 \text{ m}\cdot\text{s}^{-1}$  during the operation  
 192 period.

## 193 4 Validation of the proposed numerical framework

194 The atmosphere-soil and soil-HGHE interactions are separately evaluated to validate  
 195 the atmosphere-soil-HGHE interaction in our numerical simulation framework. A brief  
 196 verification is shown in this section, the detailed verification for the numerical simulation  
 197 model is provided in Tang and Nowamooz (2020).

198 The atmosphere-soil interaction was evaluated by using a local instrumented temper-  
 199 ature probe (Lin et al. 2020). Figure 6 shows the comparison of the numerical prediction  
 200 for a duration of 3 years from July 2014 to July 2017. The comparison shows that the nu-  
 201 merical framework is capable to predict the soil temperature with the Root-Mean-Square  
 202 Error (RMSE) value of  $1.6 \text{ }^\circ\text{C}$ , proving that atmosphere-soil interaction in the numerical  
 203 simulation predict reasonably well the in-situ measurement.

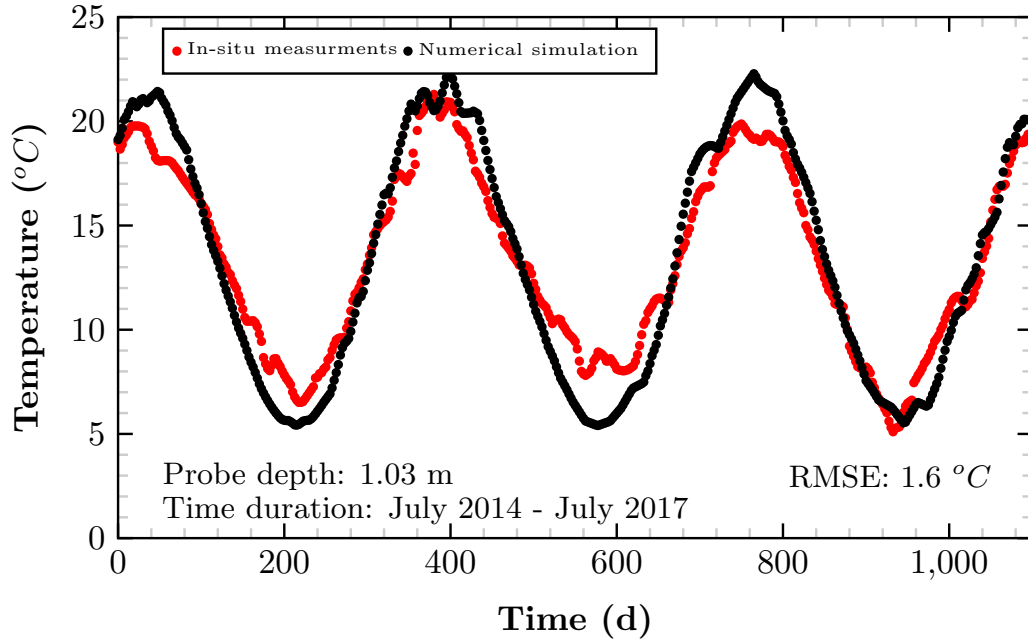


Figure 6: Comparison between the numerical predictions and the in-situ measurements for 3 years from July 2014 to July 2017 (Lin et al. 2020).

204 The soil-HGHE interaction was evaluated by an indoor experiment performed by Yoon  
 205 et al. (2015). Figure 7 shows the comparison between the experiment and prediction for  
 206 the carrying fluid outlet temperatures. A good correspondence between the experiment  
 207 and prediction proves that the proposed numerical model considers appropriately the  
 208 soil-HGHE interaction in its framework.

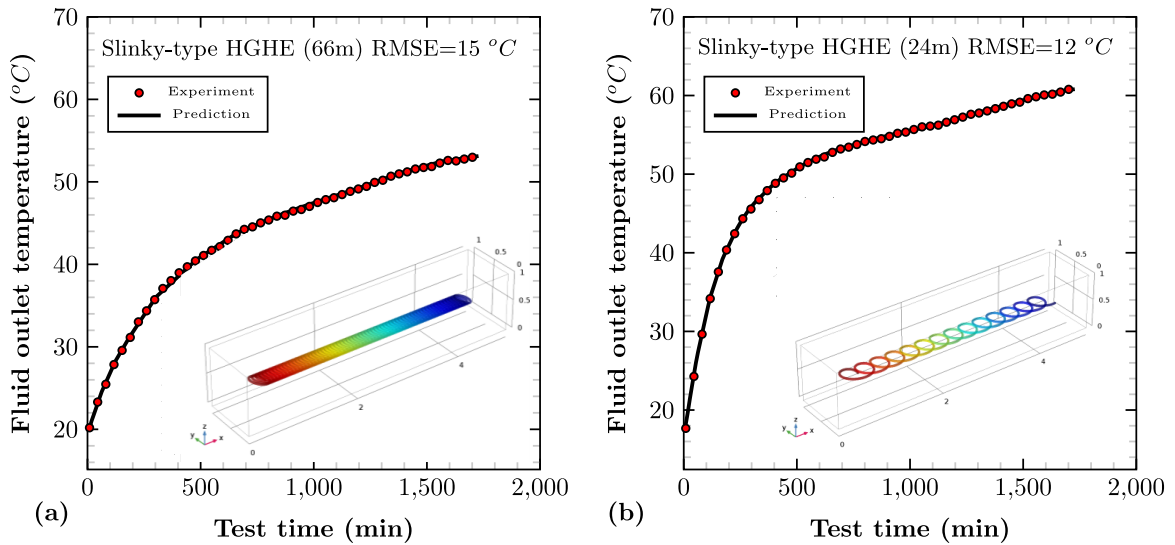


Figure 7: The comparison between the experiment and prediction for the carrying fluid outlet temperatures: (a) slinky-type HGHE with a total pipe length of 24 m and (b) slinky-type HGHE with a total pipe length of 66 m.

## 5 Comparison of performances of HGHE installed in the local and compacted backfill soils

The numerical simulations consider the atmosphere-soil-HGHE interaction in its framework. Tang and Nowamooz (2020) proposed a numerical framework for the atmosphere-soil-HGHE interaction. To avoid the repetition of the numerical framework, some principal equations of this numerical framework are reported in Appendix (Figure 16 and Table 4). To show the suitable hydro-thermal efficiency of backfill material, the performance of installed HGHE is also compared to the same system installed in the local sandy loam (Tang and Nowamooz 2018a). The system has been designed to extract the shallow geothermal energy. Therefore, a heating scenario is considered according to the local climate condition presented in section 3.2. The HGHE works from the end of Autumn season up to the end of Winter season (Figure 4a). During working times, a fluid with the inlet temperature of  $1\text{ }^{\circ}\text{C}$  circulated through the HGHE to exploit the geothermal energy. The inlet temperature of  $1\text{ }^{\circ}\text{C}$  is conventionally selected because of the thermal performance of the HGHE system. The HGHE is installed in compacted backfill and local soil in which their hydrothermal properties were presented in Tables 1 and 2 respectively.

During the service time of the HGHE, the Total Extracted Energy (TEE) can be obtained with time ( $t$ ) by the following equation:

$$TEE = \int A\rho_f u_f C_{p-f} (T_{out} - T_{in}) dt \quad (6)$$

where  $T_{in}$  is the fluid inlet temperature ( $^{\circ}\text{C}$ ),  $T_{out}$  is the fluid outlet temperature ( $^{\circ}\text{C}$ ),  $A$  is the pipe inner cross-sectional area ( $\text{m}^2$ ),  $\rho_f$  is the fluid density ( $\text{kg}\cdot\text{m}^{-3}$ ),  $C_{p-f}$  is the fluid specific heat capacity ( $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ ) and  $u_f$  is the fluid flowing velocity ( $\text{m}\cdot\text{s}^{-1}$ ).

The mesh number and time step verifications for the model are additionally brought out. Four mesh numbers indicating 38826, 53654, 78383 and 117866 are taken into account. Five time steps representing 1.5, 1.25, 1, 0.75 and 0.5 days are compared to choose the optimal one. The results show that there is a decrease accuracy of the TEE with the decrease of mesh number and increase of time step. The results show that the accuracy

235 of the numerical simulation model could be satisfied with the mesh number of 78383 and  
 236 the time step of 1 day (Figure 8).

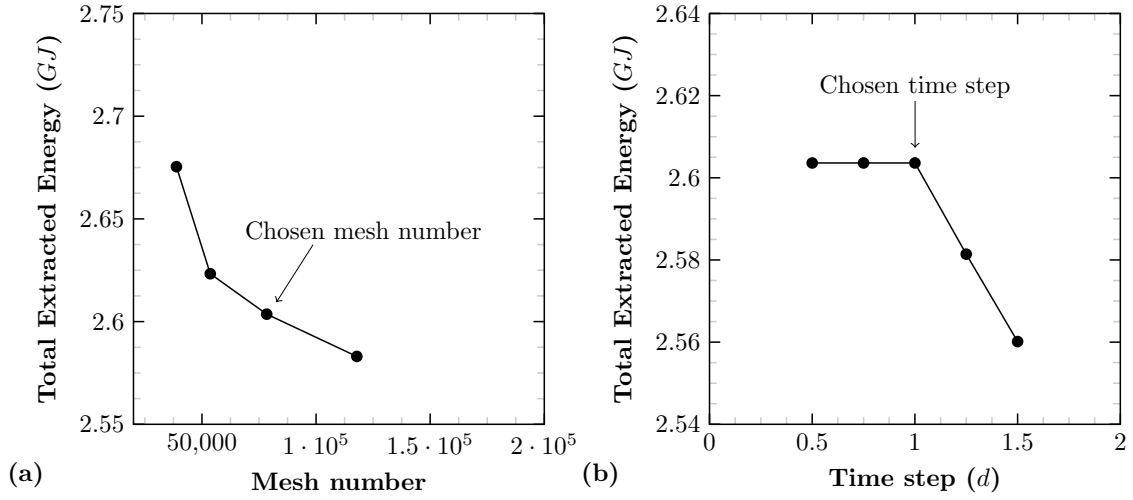


Figure 8: (a) mesh number and (b) time step verifications for the numerical simulation model.

237 Figure 9a shows the TEE of the HGHE during its annual working period for the local  
 238 and compacted backfill soils. It shows that the installed HGHE can extract 2.95 GJ and  
 239 2.49 GJ of energy after 1 year respectively for compacted backfill and local soil. It shows  
 240 that the compacted backfill soil increases 18.5% the system performance which is mainly  
 241 due to its higher initial thermal conductivity (Figure 9b).

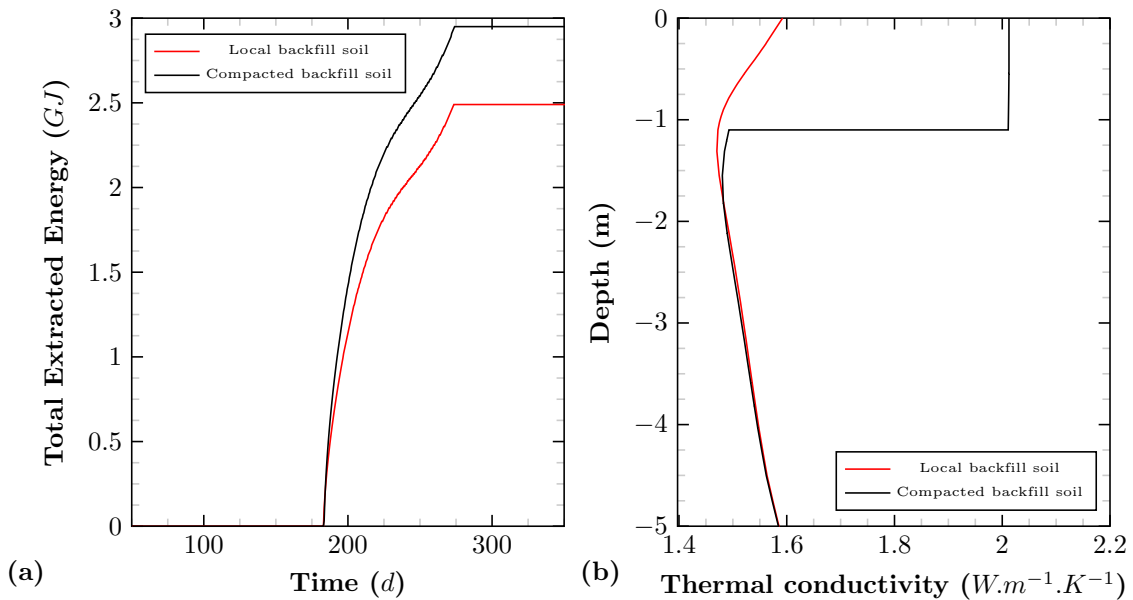


Figure 9: (a) the extracted energy with time during the service period of the HGHE for compacted backfill and local soils installed at the depth of 1 m, (b) the initial thermal conductivity profiles for the local and compacted backfill soils.

242 The whole simulation results show that the hydrothermal characteristics of backfill ma-  
243 terial are highly better than the local soil. It is recommended to use this backfill material  
244 in the HGHE system however it adds some costs for its excavation and transportation.  
245 Therefore, the geotechnical investigations of the local materials are crucial to conclude if  
246 they should be substituted by a backfill material.

## 247 **6 Heat storage effect on the performance of HGHE installed in** 248 **the compacted backfill soil**

249 In this section, the effect of thermal energy storage during summer on the HGHE  
250 performance installed in different depths compacted backfill soil is investigated. The  
251 results are compared to the original system with no heat storage (called Nsto scenario in  
252 this section).

### 253 **6.1 Energy storage scenarios and installation depths**

254 The context of thermal energy storage increases the performance of the HGHE by  
255 increasing the temperature of ground. Therefore, during summer, a fluid with higher  
256 temperature than the ground can circulate through the HGHE to exchange the tempera-  
257 ture with surrounding soil. The stored heat is expected to be released during winter. The  
258 stored energy during summer season is extracted by a circulating fluid with a temperature  
259 of  $1^{\circ}C$  in the HGHE during winter. The system stops working at the end of Winter.

260 To store thermal energy in soil during summer season and use it in winter, two different  
261 scenarios are investigated in this study:

#### 262 a) First scenario (StoA)

263 A reservoir of carrying fluid is exposed to exterior temperature and then the carrying  
264 fluid circulates in HGHE during summer. Therefore, the inlet temperature in 3 months  
265 of summer is the ambient temperature (scenario StoA) as presented in Figure 10 (tem-  
266 peratures of 0 to 92 days). This system is in relaxation in Autumn (from 92nd to 183rd  
267 day), therefore no fluid flow will be circulated through the system. When Winter comes



268 (from 183rd to 274th day), a fluid flow with inlet temperature of  $1^{\circ}\text{C}$  will be circulated.  
 269 Again the system is in relaxation in Spring (from 274rd to 365th day) (Table 3).

270 b) Second scenario(Sto50)

271 Solar panels absorb the solar energy and the energy can be used to heat the subsurface  
 272 soil in summer while a fluid with a constant inlet temperature is circulating in the HGHE.  
 273 Therefore, the inlet temperature in 3 months of summer is a constant temperature of 50  
 274  $^{\circ}\text{C}$  (Sto50) as presented in Figure 10. The system works the same way as the ambient  
 275 temperature storage scenario except that the inlet temperature is  $50^{\circ}\text{C}$  in Summer season  
 276 (Table 3).

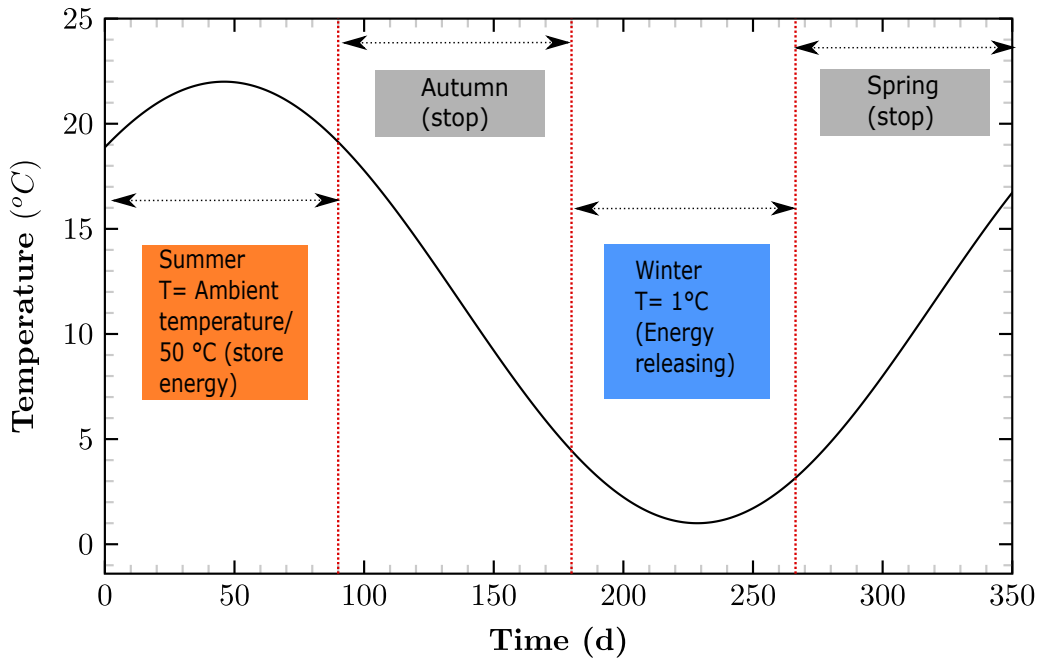


Figure 10: Operation mode for the HGHE over one year.

Table 3: Imposed temperature of inlet fluid for StoA and Sto50.

Scenario	Summer (0 to 92 <sup>th</sup> days)	Autumn (92 <sup>nd</sup> to 183 <sup>rd</sup> day)	Winter (183 <sup>rd</sup> to 274 <sup>th</sup> day)	Spring (274 <sup>rd</sup> to 365 <sup>th</sup> day)
StoA	Ambient tempera- ture Figure 4a	Relaxation	$1^{\circ}\text{C}$	Relaxation
Sto50	$50^{\circ}\text{C}$	Relaxation	$1^{\circ}\text{C}$	Relaxation

277

278 Due to the interaction with ground surface, the stored energy during relaxation seasons  
 279 is dissipated into the atmosphere. If the HGHE is installed close to the land surface, a

280 higher amount of stored energy can be dissipated. Therefore, three depths of 1, 1.5 and  
 281 2 m beneath land surface are investigated for both scenarios to study the influence of  
 282 installation depth on the HGHE performance.

## 283 6.2 Simulation results

284 a) Scenario 1 (StoA) compared to scenario with no heat storage (Nsto)

285 Figure 11 shows the pipe outlet temperature with time at the installation depths of  
 286 1, 1.5 and 2 m for the first scenario (StoA) compared to the outlet temperatures of the  
 287 original HGHE with no heat storage (Nsto) presented in section 5. The figure shows the  
 288 fluid outlet temperature decreases abruptly with the working of the HGHE. Afterwards,  
 289 the fluid temperature generally decreases and starts to increase with warmer climate. In  
 290 addition, the figure shows that outlet temperature increases slightly by depth.

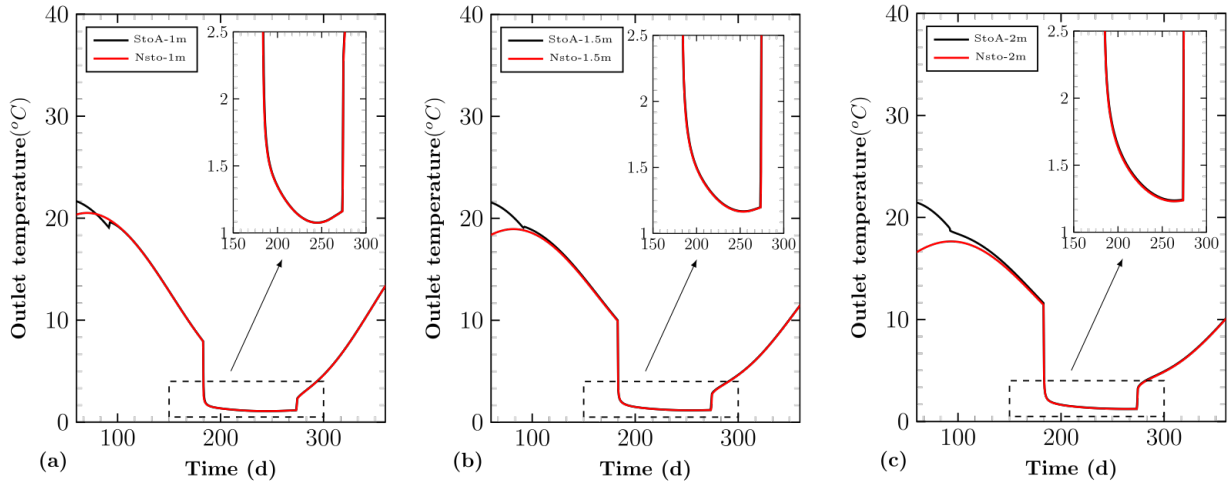


Figure 11: Outlet temperature comparison of the storage scenario (ambient temperature) and the non-storage scenario for three installation depths (a) 1m, (b) 1.5m and (c) 2m.

291 b) Scenario 2 (Sto50) compared to scenario with no heat storage (Nsto)

292 Figure 12 shows the outlet temperature for the second storage scenario (Sto50) at  
 293 three installation depths compared to the outlet temperatures of the original HGHE  
 294 with no heat storage (Nsto) presented in section 5. The figure shows that the ground  
 295 temperature is obviously improved in summer, and the deeper the installation depth, the  
 296 larger difference between the outlet temperatures of the scenario considering and non-  
 297 considering the energy storage in summer.

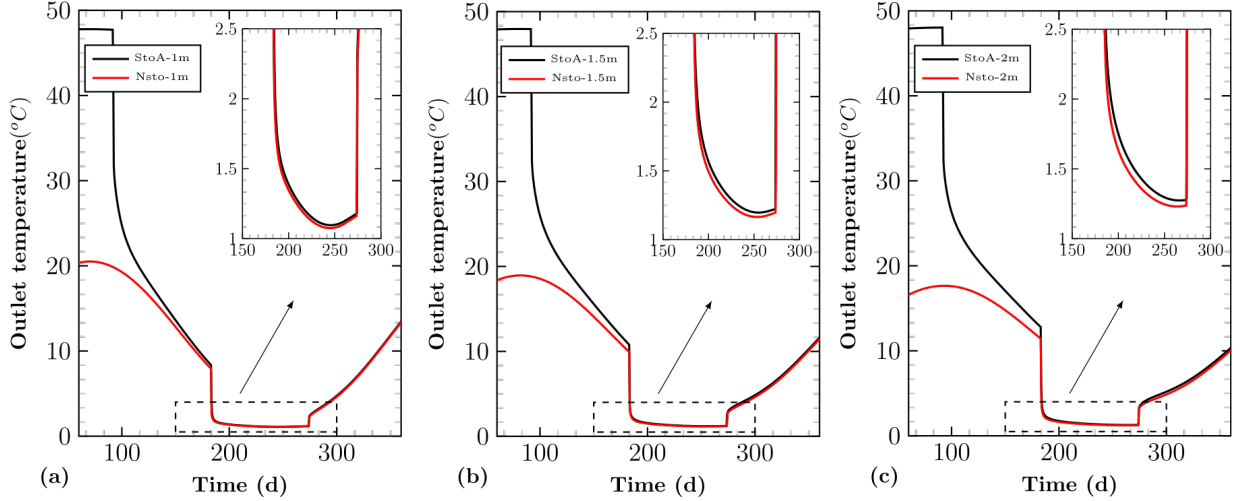


Figure 12: Outlet temperature comparison of the storage scenario ( $50\text{ }^{\circ}\text{C}$  of inlet temperature during summer) and the non-storage scenario for three installation depths (a) 1m, (b) 1.5m and (c) 2m.

As presented in section 5, the backfill soil is recommended for the good performance of the HGHE system. In this section, the different energy storage scenarios and the installation depths are also investigated. To optimize the system performance, it is necessary to compare these different configurations together.

## 7 Comparison of the two energy storage scenarios

The surrounding temperatures of the HGHE installed at the depth of 2 m in the end of Summer, Autumn and Winter are shown in Figure 13. The figure shows that the soil temperature has been clearly improved in the scenario with  $50\text{ }^{\circ}\text{C}$  of fluid inlet temperature in Summer (Sto50), while the surrounding temperature improves negligibly with the ambient temperature storage scenario (StoA). Specifically, soil temperature has been improved  $27\text{ }^{\circ}\text{C}$  and  $3\text{ }^{\circ}\text{C}$  respectively at the depth of 2 m at the end of Summer and Autumn with the energy storage scenario (Sto50).

By using equation 6, the corresponding extracted energies can be exploited with time for both scenarios as presented in Figure 14. The results show that the heat storage can improve the TEE and the improvement increases with depth in both scenarios. This increase is more evident for the scenario Sto50. Specifically, for the installation depth of 1 m, this increase is  $0.34\text{ GJ}$  (13.7%) compared to  $0.0\text{ GJ}$  (0.0%). When the installation

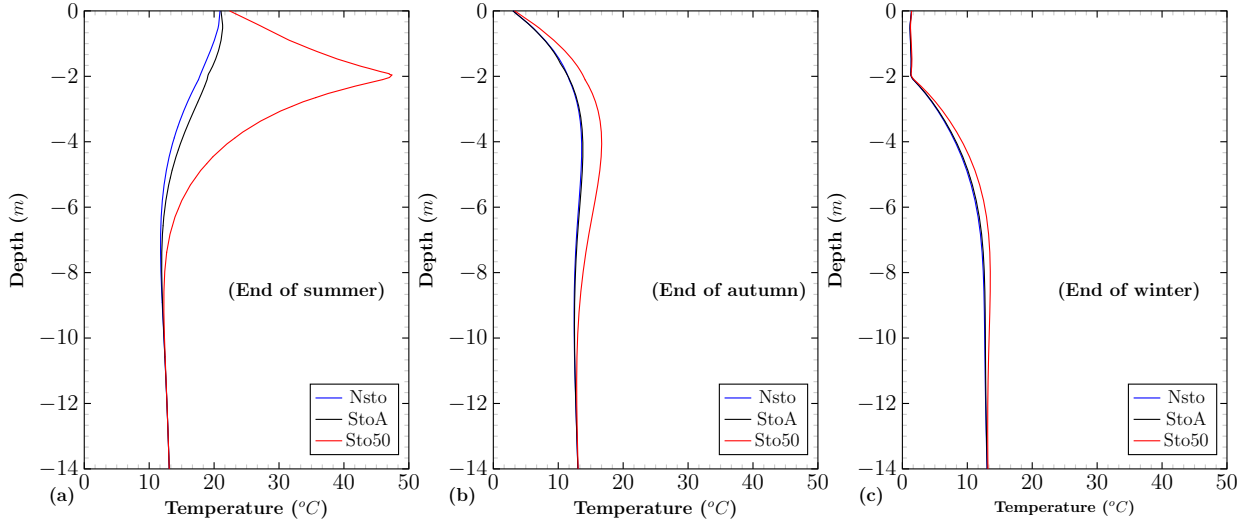


Figure 13: Temperature profiles at the end of (a) Summer , (b) Autumn and (c) Winter.

315 depth increases from 1 to 2  $m$ , the final improvement of the TEE increases from 0.0 GJ  
 316 to 0.12 GJ (0.0 to 4.8%) for the first scenario StoA (Figure 14a) while it increases from  
 317 0.34 GJ to 1.03 GJ (13.7 to 41.4%) for the second scenario (Sto50).

318 Figure 15 compares the annual TEE values of the aforementioned heat storage scenarios  
 319 (StoA and Sto50) with the TEE values of the original scenario without heat storage  
 320 (Nsto). The figure shows that the HGHE can be highly improved by adopting an inlet  
 321 fluid temperature of  $50^{\circ}C$  in summer while the ambient inlet temperature produces less  
 322 amelioration in the HGHE performance.

323 The simulations show clearly that a higher installation of the backfill material accom-  
 324 panied with the Sto50 scenario produce the best performance for the HGHE. However  
 325 , some additional costs are to be considered for a deeper installation. Therefore, it is  
 326 recommended to add a cost overview for the different installation depths of the backfill  
 327 material compared to local materials to find an optimized depth for the HGHE system.

## 328 8 Conclusions

329 This work brings some insights into the selection of the backfill soil on the performance  
 330 of a HGHE. Moreover, two energy storage scenarios and three installation depths have  
 331 been adopted to investigate the HGHE performance. A well-known compacted backfill

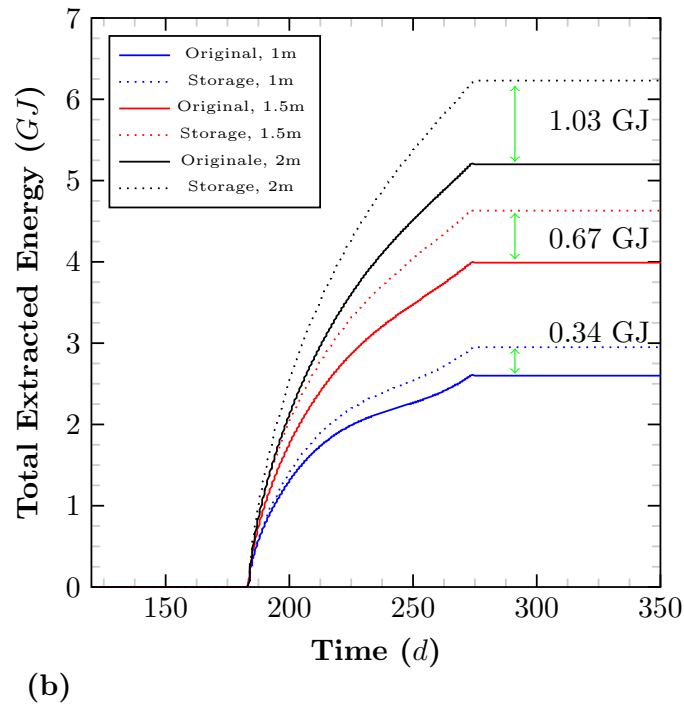
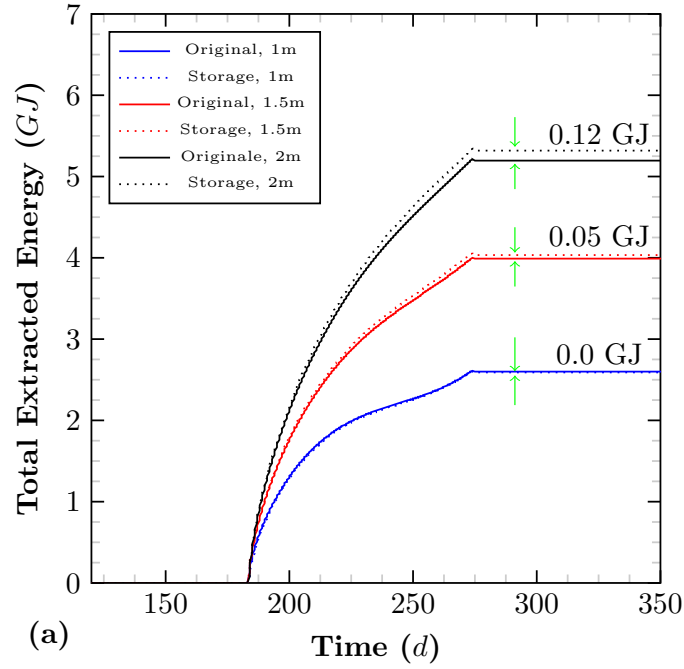


Figure 14: Total extracted energy with time of (a) first scenario (StoA) and (b) second scenario (Sto50) compared to the original HGHE system (Nsto).

332 soil was used to improve the performance of a HGHE system installed in the east of  
 333 France. The hydrothermal properties of the backfill soil were first injected in a numerical  
 334 framework considering the atmosphere-soil-HGHE interaction. The simulations results  
 335 showed that the compacted backfill material provided an increase 18.5% in the HGHE

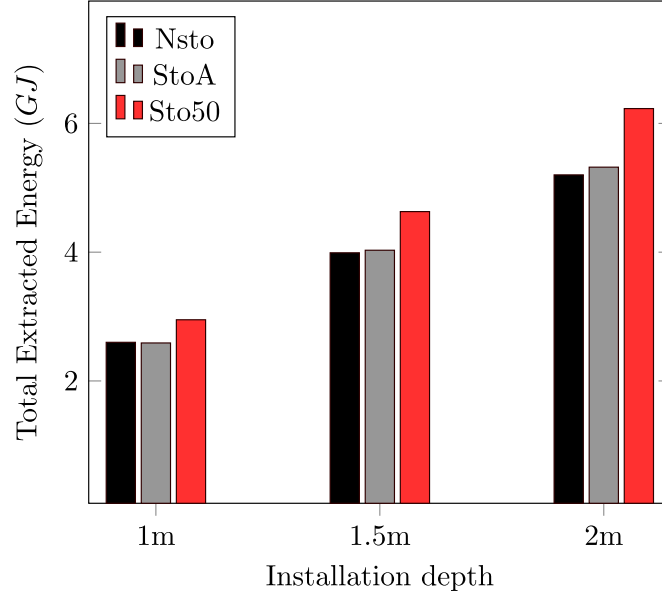


Figure 15: Comparison between the heat storage scenarios (StoA and Sto50) with non-storage scenario (Nsto) at three different installation depths.

336 performance compared to the existing local soil. To improve the HGHE performance,  
 337 two heat storage scenarios at three different installation depths were studied. The results  
 338 showed that an inlet fluid temperature of 50 °C in summer increased highly the system  
 339 performance (13.7 to 41.4%) while the improvement was less significant (0 to 4.8%) for  
 340 the ambient inlet temperature. A deeper installation depth increased the total extracted  
 341 energy (TEE) but increases the installation costs. This study has focused only on one  
 342 metrological region and further analysis are still necessary to combine the meteorological  
 343 conditions with the selection of the backfill material used in the HGHE systems.

## 344 A Appendix: Governing Equations

345 Figure 16 shows a schematic diagram of the concerning phenomenon in HGHE engi-  
 346 neering. The necessary governing equations considering the atmosphere-soil-HGHE inter-  
 347 action are constituted of 4 parts: a) the soil surface energy balance; b) the soil surface  
 348 water balance; c) the hydrothermal transfer in subsurface soil and d) the heat transfer  
 349 in pipe. All these equations were already published in Tang and Nowamooz (2020). A  
 350 summary of these equations is presented in Table 4.

351 In Table 4,  $R_n$  is the net radiation heat flux ( $W.m^{-2}$ ),  $H$  is the sensible heat flux

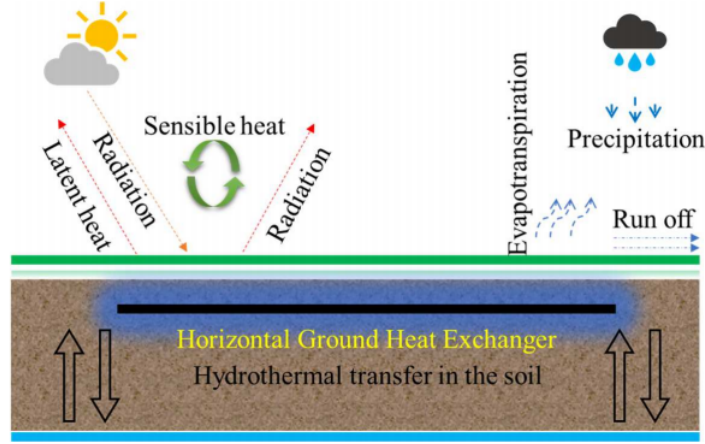


Figure 16: Comparison between the heat storage scenarios (StoA and Sto50) with non-storage scenario (Nsto) at three different installation depths.

352 ( $W.m^{-2}$ ),  $LE$  is the latent heat flux ( $W.m^{-2}$ ),  $G$  is the ground heat flux ( $W.m^{-2}$ ),  $a_l$  is  
 353 the surface albedo,  $R_s$  is the shortwave radiation ( $W.m^{-2}$ ),  $R_a$  is the incoming longwave  
 354 radiation ( $W.m^{-2}$ ),  $\varepsilon\sigma T_s^4$  is the outgoing longwave radiation ( $W.m^{-2}$ ),  $\varepsilon$  is the soil sur-  
 355 face emissivity,  $\sigma$  is Stephan-Boltzman constant ( $W.m^{-2}.k^{-4}$ ),  $T_s$  is the soil temperature  
 356 ( $K$ ),  $\rho_a$  is the air density ( $kg.m^{-3}$ ),  $C_{P-a}$  is the air specific heat capacity ( $J.kg^{-1}.K^{-1}$ ),  
 357  $r_a$  is the aerodynamic resistance to heat transfer ( $s.m^{-1}$ ),  $P$  is the rainfall rate ( $mm.s^{-1}$ ),  
 358  $E_p$  is the evaporation potential ( $mm.s^{-1}$ ),  $LAI$  is the leaf area index,  $h_c$  is the displace-  
 359 ment height is linear o the vegetation height ( $m$ ),  $W_r$  is the water run off,  $E$  is the actual  
 360 evaporation,  $W_i$  is the infiltration,  $\rho_w$  is the water density ( $kg.m^{-3}$ ),  $\Psi$  is the specific  
 361 moisture capacity ( $m^{-1}$ ),  $H_p$  is the suction head ( $m$ ),  $t$  is the time ( $s$ ),  $K$  is the saturated  
 362 hydraulic conductivity ( $m.s^{-1}$ ),  $k_r$  is the relative hydraulic conductivity,  $D$  is the eleva-  
 363 tion head ( $m$ ),  $H_k$  is the kinetic head ( $m$ ),  $\rho_s$  is the soil density ( $kg.m^{-3}$ ),  $C_{p-s}$  is the  
 364 soil heat capacity ( $J.kg^{-1}.K^{-1}$ ),  $C_{p-w}$  is the water specific heat capacity ( $J.kg^{-1}.K^{-1}$ ),  
 365  $u_w$  is the water velocity in soil ( $m.s^{-1}$ ),  $Q_s$  is the soil heat source ( $W.m^{-3}$ ),  $A$  is the pipe  
 366 inner cross-sectional area ( $m^2$ ),  $\rho_f$  is the fluid density ( $kg.m^{-3}$ ),  $C_{p-f}$  is the fluid specific  
 367 heat capacity ( $J.kg^{-1}.K^{-1}$ ),  $T_f$  is the fluid temperature ( $^{\circ}C$ ),  $u_f$  is the fluid flowing ve-  
 368 locity ( $m.s^{-1}$ ),  $k_f$  is the fluid thermal conductivity ( $W.m^{-1}.K^{-1}$ ),  $f_D$  is the Darcy friction  
 369 factor,  $d_h$  is the hydraulic diameter ( $m$ ) and  $Q_{wall}$  is the energy from the surrounding  
 370 media ( $W.m^{-1}$ ),  $h_{int}$  is the film heat transfer coefficient ( $W.m^{-2}.K^{-1}$ ),  $Z$  is the pipe inner

371 perimeter ( $m$ ) and  $T_{i-p}$  is the inner pipe temperature ( $^{\circ}C$ ).

Table 4: Principal equations of atmosphere-soil-HGHE interaction.

Type of interaction	Principal equation
soil surface energy balance (Turc 1954; Pike 1964; Monteith 1965; Allen et al. 1989; Gerrits et al. 2009; Chalhoub et al. 2017; Chen and Buchberger 2018)	$R_n + H - LE - G = 0$ $R_n = (1 - a_l)R_s + (R_a - \varepsilon\sigma T_s^4)$ $H = \rho_a C_{p-a}(T_a - T_s)/r_a$ $E = P.[1 + (E_p/P)^{-2}]^{1/2}$ LAI=24. $h_c$ for clipped grass or LAI=5.5+1.5 ln $h_c$ for other crops
Soil surface water balance (Dietrich et al. 2016)	$P = W_r + E + W_i$
Richard equation for hydraulic transfer in soil (Wind 1966; Mualem 1976; van Genuchten 1980)	$\rho_w \cdot \Psi \cdot \frac{dH_P}{dt} + [-K \cdot k_r \cdot \nabla \cdot \rho_w \cdot (H_P + D + H_k)] = 0$
Hydrothermal transfer in subsurface soil (Nowamooz et al. 2015; Nikoosokhan et al. 2015; Tang and Nowamooz 2018a; Tang and Nowamooz 2018b)	$\rho_s C_{p-s} \frac{dT_s}{dt} = \nabla \cdot (k_s \nabla T_s) + \nabla \cdot (\rho_s C_{p-s} u_w T_s) + Q_s$
Heat transfer in pipe	$A\rho_f C_{p-f} \frac{dT_f}{dt} + A\rho_f C_{p-f} u_f \cdot \nabla T_f = \nabla \cdot A k_f \nabla T_f + f_D \frac{\rho_f A}{2d_h}  u_f  u_f^2 + Q_{wall}$ $Q_{wall} = h_{int} \cdot Z \cdot (T_{i-p} - T_f)$

Table 5: Parameters for the soil surface energy balance.

Parameter	Description	Value	Unit
$a_l$	Albedo	0.25	-
$\varepsilon$	Soil emissivity	0.97	-
$\sigma$	Stephan-Boltzman constant	$5.67 \times 10^{-8}$	$W \cdot m^{-2} \cdot K^{-4}$
$\rho_a$	Air density	1.25	$kg \cdot m^{-3}$
$C_{p-a}$	Air specific heat capacity	$1.00 \times 10^3$	$J \cdot kg^{-1} \cdot K^{-1}$
$z_m$	Height to collect the meteorological data	2.00	$m$
$h_c$	Grass height	0.06	$m$
$k$	von Karman constant	0.41	-
$L$	Latent heat of vaporization	2.26	$J \cdot kg^{-1}$
$p_{at}$	Atmospheric pressure	102000	$Pa$
$r_{mw}$	Molecular weight of water vapor to dry air	0.62	-
$r_1$	Stomatal resistance of a single leaf	100	$s \cdot m^{-1}$



## Nomenclature

$A$	U-pipe cross-sectional area, $m^2$
$a_l$	surface albedo
$C_p$	specific heat capacity, $J.kg^{-1}.K^{-1}$
$C_v$	volumetric heat capacity, $J.m^{-3}.K^{-1}$
$D$	elevation head, $m$
$E_p$	evaporation potential, $kg.m^{-2}.s^{-1}$ or $mm.s^{-1}$
$d_h$	inner diameter of the U-pipe, $m$
$f_D$	Darcy friction factor
$G$	total heat flux through land surface, $W.m^{-2}$
$h_c$	vegetation height, $m$
$h_{int}$	heat transfer coefficient, $W.m^{-2}.K^{-1}$
$H$	sensible heat flux, $W.m^{-2}$
$H_k$	kinetic head, $m$
$H_p$	water potential or suction head, $m$
$k$	thermal conductivity, $W.m^{-1}.K^{-1}$
$k_r$	relative hydraulic conductivity
$K$	hydraulic conductivity, $m.s^{-1}$
$l$	pore connectivity parameter
$L$	latent heat of vaporization for water, $J.kg^{-1}$

$LAI$	leaf area index
$n$	independent parameter
$P$	rainfall rate, $mm.s^{-1}$
$P_{at}$	atmospheric pressure, $Pa$
$Q_s$	soil heat source, $W.m^{-3}$
$Q_{wall}$	heat from the surrounding, $W.m^{-1}$
$r_1$	stomatal resistance of a single leaf, $s.m^{-1}$
$r_a$	aerodynamic resistance to heat transfer, $s.m^{-1}$
$r_c$	crop canopy resistance, $s.m^{-1}$
$r_{mw}$	molecular weight of water vapor to dry air
$R_n$	net radiation, $W.m^{-2}$
$R_s$	shortwave radiation, $W.m^{-2}$
$S_e$	relative saturation of soil
$S_r$	saturation of soil
$t$	time, $s$
$T$	temperature, $^{\circ}C$ or $K$
$T_{in}$	inlet temperature, $^{\circ}C$
$T_{out}$	outlet temperature, $^{\circ}C$
$T_s$	land surface temperature, $K$
$u$	velocity, $m.s^{-1}$

$w$  water content

$W_i$  infiltration,  $mm.s^{-1}$

$W_r$  water run off,  $mm.s^{-1}$

375

$x_s$  gravimetric sand content

$Z$  U-pipe inner perimeter,  $m$

$z_m$  height for measuring meteorological conditions,  $m$

376

#### Greek symbols

$\alpha$  independent parameter,  $m^{-1}$

$\gamma_d$  soil dry unit weights,  $kN.m^{-3}$

$\gamma_s$  soil specific unit weights,  $kN.m^{-3}$

377

$\varepsilon$  soil surface emissivity

$k$  von Karman constant

$\rho$  density,  $kg.m^{-3}$

$\sigma$  Stephan-Boltzman constant,  $W.m^{-2}.K^{-4}$

378

#### Subscripts

a air

f carrying fluid

i-p inner pipe wall

379

r residual

s soil

sat saturated

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