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► **To cite this version:**

Mathias Cuny, Jian Lin, Monica Siroux, Christophe Fond. Influence of an improved surrounding soil on the energy performance and the design length of earth-air heat exchanger. Applied Thermal Engineering, 2019, 162, pp.114320. 10.1016/j.applthermaleng.2019.114320 . hal-03859298

**HAL Id: hal-03859298**

<https://hal.science/hal-03859298v1>

Submitted on 29 Nov 2024

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# Influence of an improved surrounding soil on the energy performance and the design length of earth-air heat exchanger

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## Abstract

European directive 31/2010/EU imposes a reduction of primary energy consumption in the building sector. An Earth-air heat exchanger (EAHE) is a renewable energy system that can respond in part to this problem. This system uses soil temperature to cool or heat ventilated air for a building. However, the design of the EAHE depends on thermo-physical characteristics of the surrounding soil. A numerical study is carried out to investigate the energy performance and the design length under influence on an improved surrounding soil. Six EAHE configurations, of three different lengths (20 m, 40 m and 60 m) and two different types of surrounding soils, are simulated: the standard soil used (fine sand, sand) and an improved surrounding soil (a mix between fine sand and 3 % of bentonite, named bent-sand). Weather conditions and soil thermo-physical properties used in the simulations are derived from the measurements recorded in an experimental EAHE. The results show that the addition of bentonite in the sand surrounding soil improves the EAHE's energy performance and that the design length of an EAHE can be reduced for a defined power.

**Key words:** renewable energy, earth-air heat exchanger, surrounding soil, bentonite.

## Nomenclature

### Symbols

$c_p$  specific heat,  $J.kg^{-1}.K^{-1}$

$C$  volumetric heat capacity,  $J.m^{-3}.K^{-1}$

$E$  thermal energy, Wh

$h$	convective heat exchange coefficient, $\text{W.m}^{-2}.\text{K}^{-1}$
$L$	length of the EAHE, m
$r$	radius of the pipe, m
$t$	time, s
$T$	temperature, $^{\circ}\text{C}$
$v$	air velocity, $\text{m.s}^{-1}$
$z$	pipe's depth, m

#### Greek symbols

$\lambda$	thermal conductivity, $\text{W.m}^{-1}.\text{K}^{-1}$
$\phi$	thermal power, W
$\omega$	soil moisture content, $\text{kg.kg}^{-1}$

#### Subscripts and superscripts

diff	difference
eq	equivalent
f	final
g	ground
int	interior

#### Abbreviations

EAHE	earth-air heat exchanger
COP	coefficient of performance
NSB	natural soil backfill
HVAC	Heating, ventilation and air conditioning

29

30

31 **1. Introduction**

32 To fight against greenhouse gas emissions, one of the European Union's strategies is to decrease  
33 the energy consumption of buildings [1], which represents about 40 % of total consumed primary  
34 energy [2]. In developed countries, heating, ventilation and air conditioning (HVAC) represents  
35 approximately 68 % of primary energy consumed in the residential sector [2]. Therefore, one  
36 solution for reducing energy consumption is to combine HVAC systems with renewable  
37 resources such as geothermal energy and in particularity with an earth-air heat exchanger  
38 (EAHE). An EAHE decreases primary energy consumption of an HVAC system by 29 % in  
39 winter and between 36 % and 46 % in summer [3].

40 Moreover, EAHE preheats or cools ventilated air into buildings. In summer, it provides air at a  
41 comfortable temperature [4]. In winter, it becomes more effective when outside air temperature  
42 is lower. For example, in very cold climates such as in the north of China, its heating power is 8  
43 kW for an inlet air temperature of -25 °C and 1 kW for 0 °C [5]. An EAHE combined with a  
44 dual-flow controlled motorized ventilation system, the total ventilation system's coefficient of  
45 performance (COP) doubles compared to a system without EAHE and reaches 16 [5]. EAHE  
46 systems are appropriate for most climates like hot and arid climate or cold climate [6] as well as  
47 contrasting climates (very hot in summer and cold in winter), as in Mexico [7].

48 Despite the advantages of the EAHE system, the difficulty lays in the sensitivity of its energy  
49 performance to geometric parameters, pipe configuration and operation mode [8]. The geometric  
50 parameters concern air speed, pipe length, pipe diameter and buried depth [9-10]. Concerning  
51 pipe configuration, it is not necessary to use an EAHE of excessive length. Indeed, the pressure  
52 losses of ventilated air become significant which leads to the overconsumption of the fan.  
53 Parallel exchanger pipes are preferred in this case [11]. The influence of an EAHE's operation  
54 mode has also been studied. The intermittent mode ensures a high energy efficiency compared to  
55 the continuous mode [12]. These studies show that the energy performance of an EAHE can be  
56 optimized by design parameters. However, predicted energy performance is not necessarily  
57 assured. It strongly depends on thermo-physical characteristics of the soil around the EAHE

58 pipe. In particular, a soil, with high thermal conductivity and high specific heat, is an ideal  
59 location for burying a ground heat exchanger [13].

60 Recent scientific studies focus on the energy impact of soil thermo-physical properties. The role  
61 of soil compactness has been studied for a hot and arid climate in [14]. The authors showed that  
62 relative soil compactness greater than 90 % introduces cooler outlet air temperatures when soil  
63 temperature is below 25 °C and outside temperature is greater than 50 °C. Moreover, soil  
64 moisture content influences the energy performance. Compared with dry soil, the COP of an  
65 EAHE can be improved by 15.8 % and 22.9 % for a soil moisture content of 5 % and 15 %,  
66 respectively [15]. The outlet air temperature of a 40 m length EAHE in dry soil is equal to that of  
67 a 26 m length EAHE in soil with a water content of 15 % [16]. Furthermore, the nature of the  
68 surrounding soil has an impact. The mixture of sand and bentonite keeps high soil moisture  
69 content at a constant level thus improving energy performance [17]. Similar studies were carried  
70 out for other types of geothermal heat exchangers. In [18], spiral exchangers were buried in  
71 different types of surrounding soil: loamy sand, a mix between bentonite and sand, and pure  
72 sand. The results indicated that the system's performance depends mainly on soil moisture  
73 content and soil type. For vertical geothermal exchangers, many studies were carried out to  
74 improve the thermal conductivity of grout between the exchanger pipes and the ground. In  
75 particular, the mixture between bentonite and sand makes it possible to improve heat exchange  
76 on average between 22.2 % and 31.1 % concerning a material composed of sand and clay [19].

77 The present work studies the energy performance and design length of an EAHE under the  
78 influence of an improved surrounding soil. A numerical model was used to simulate 6 EAHE  
79 systems over one entire year consisting of three different lengths (20, 40 and 60 m) and two  
80 types of surrounding soil (sand and bent-sand). The configuration parameters and weather  
81 conditions are derived from an experimental EAHE. An analysis method of simulation results is  
82 presented to evaluate energy performance. A conception criterion is introduced to evaluate the  
83 impact of improved surrounding soil: the equivalent length. The results of the numerical

84 simulations are shown and discussed in the last part. The gains at energy performance and design  
85 length by using the bent-sand surrounding soil in EAHE systems are presented at the end.

## 86 **2. Computational model**

### 87 **2.1. A 2D finite elements model**

88 This part presents the numerical model used to study the energy performance of an EAHE. In  
89 order to simulate the EAHE for a long period (one year), a numerical model developed in [17]  
90 has been extended to take into account the dynamic moisture content evolution in the  
91 surrounding soil. This model considers a 2D modelling of the ground with the EAHE and a 1D  
92 modelling of the ventilated air inside the pipe. This model divides the EAHE into several equal  
93 lengths (named portions) and it calculates the outlet air temperature of each portion by the  
94 proceeding four steps.

95 Step 1: the initial soil temperature is calculated by resolving the heat equation (1) in a vertical  
96 section using the 2D finite elements method. It permits to obtain an initial ground temperature  
97 field for the first time instant. A period of one month before the studied period has been  
98 simulated to obtain a reliable temperature field. The calculation takes into account the evolution  
99 of the ground's thermal properties which depends on the recorded soil moisture content.

$$C_g(\omega_g(t)) \frac{\partial T_g(t)}{\partial t} = \nabla \cdot (\lambda_g(\omega_g(t)) \nabla T_g(t)) \quad (1)$$

100 where  $T_g$  represents ground temperature,  $C_g$  is ground volumetric heat capacity,  $\lambda_g$  is ground  
101 thermal conductivity and  $\omega_g$  is ground moisture content.

102 Step 2: the evolution of ventilated air temperature is calculated for one portion  $\Delta x$ . For the first  
103 portion, inlet air temperature is imposed with the recorded outside air temperature. For the  
104 following portions, inlet air temperature is equal to outlet air temperature of its previous portion.  
105 The evolution of air temperature at each portion is calculated by equation (2) considering a  
106 constant ground temperature field when ventilated air passes through the current portion.

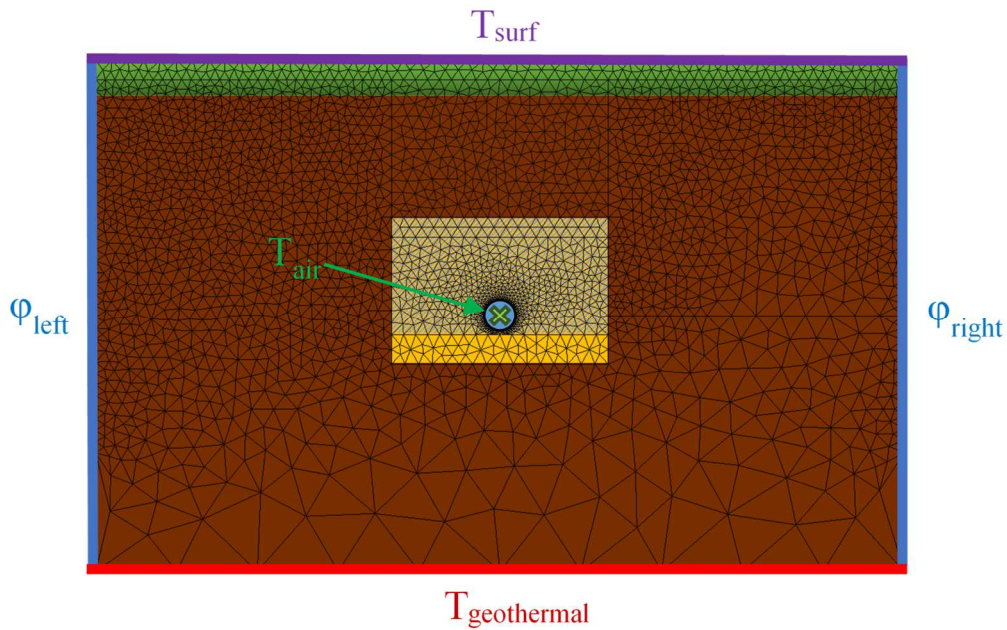
$$h_{air} \times [T_{pipe}(x, t) - T_{air}(x, t)] = v_{air} \cdot \pi \cdot r_{int}^2 \cdot C_{air} [T_{air}(x + \Delta x, t) - T_{air}(x, t)] \quad (2)$$

107 where  $h_{air}$  is the convective heat exchange coefficient of ventilated air,  $v_{air}$  is air velocity,  $C_{air}$   
 108 is air volumetric heat capacity,  $r_{int}$  is interior radius of the pipe,  $T_{pipe}$  is pipe temperature and  
 109  $T_{air}$  is ventilated air temperature.

110 Step 3: remaining at the studied portion of Step 2, a new ground temperature field is calculated  
 111 for the next time instant  $t + \Delta t$ . During one time increment of  $\Delta t = 20$  minutes, ground  
 112 temperature is calculated with equation (1) by considering simulated air temperature inside the  
 113 EAHE pipe and recorded surface temperature at the top.

114 Step 4: alternating Step 2 and Step 3 for all the portions of the EAHE, the EAHE's outlet air  
 115 temperature at the instant  $t$  and the ground temperature field are obtained for the next instant  $t +$   
 116  $\Delta t$ . Then the model returns to Step 2 to simulate the EAHE at this new time instant.

117 This approach is numerically studied with Code\_Aster® finite elements software shown. The  
 118 mesh is shown in in Figure 1. Different boundary conditions are considered. At the soil surface, a  
 119 temperature  $T_{surf}$  is imposed by measurements recorded every 20 minutes. Inside the heat  
 120 exchanger, the ventilated air temperature  $T_{air}$  of previous time instant is imposed. At the bottom,  
 121 a constant temperature represents geothermal temperature  $T_{geothermal}$  is considered at a depth of  
 122 3 m. On the lateral boundaries, 2.5 m away from the pipe's axe, thermal flows  $\varphi_{left}$  and  $\varphi_{right}$   
 123 are nulls.



124

Figure 1 : Spatial discretization of the numerical model with boundary conditions.

125

## 2.2. Input data of simulated EAHEs

126

All input data come from an experimental EAHE located at the University of Strasbourg, France.

127

This EAHE is divided into three portions with different types of surrounding soil (see Figure 2):

128

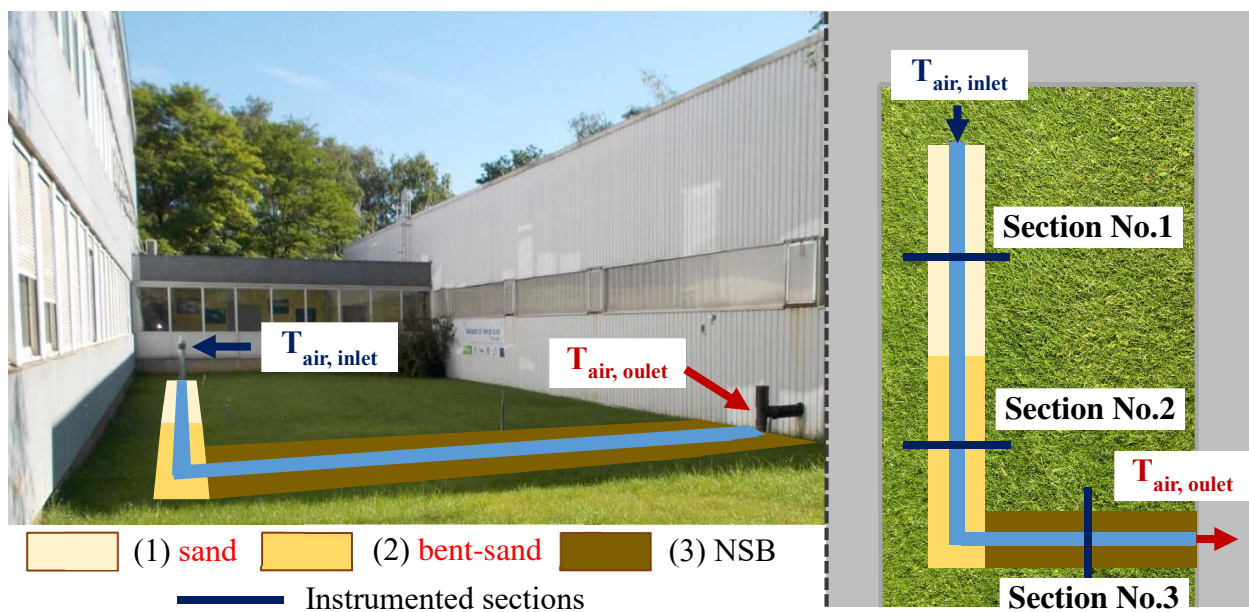
(1) sand; (2) bent-sand; and (3) natural soil backfill (NSB) composed of gravel-clay. During the

129

operation, air is extracted by a fan. Air passes through the pipe with a constant air blowing veloc-

130

ity ( $2.5 \pm 0.2 \text{ m.s}^{-1}$ ). The pipe's outer diameter is 20 cm and its inner diameter is 17 cm.



131

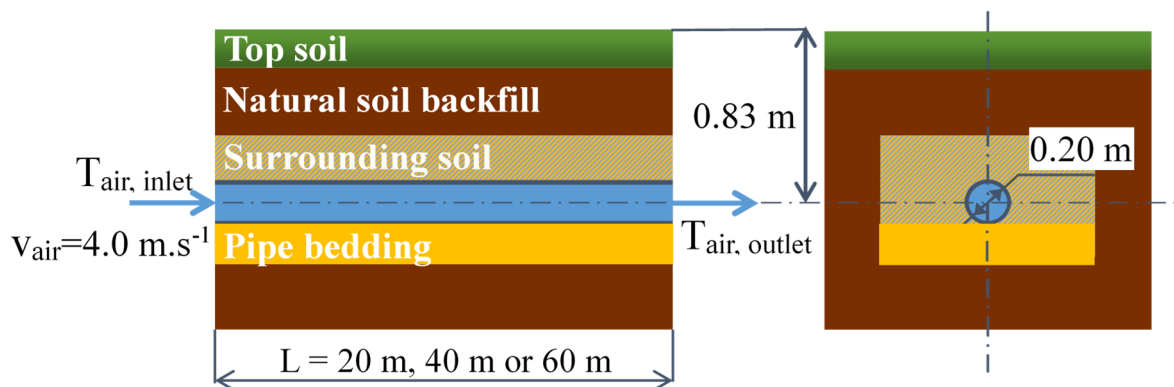
Figure 2 : Picture and birds eye view representation of the experimental EAHE with its different types of surrounding soil: (1) sand, (2) bent-sand and (3) NSB.



132 The experimental EAHE is instrumented at three vertical sections (No.1, No.2 and No.3 in Fig-  
 133 ure 2). The following elements are measured: soil temperature at different positions, air tempera-  
 134 ture inside the pipe and soil moisture content of the surrounding soil. All the temperatures are  
 135 measured with PT100 temperature sensors with a precision of 0.1 °C. Soil moisture content is  
 136 measured with a TRIME©-pico64 sensor. It is a TDR (time domain reflectometry) sensor with a  
 137 precision of 3 %. Two PT100 sensors are installed to measure inlet and outlet air temperature. All  
 138 the measurements were recorded every 20 minutes by a Keithley 3706A data logger.

### 139 2.3. Configuration of simulated EAHEs

140 The geometric parameters of portion No.1 of the experimental EAHE (shown in Figure 2) were  
 141 used in the numerical simulation. Figure 3 shows the configuration parameters of the simulated  
 142 EAHE systems.



143 *Figure 3 : Configuration parameters of the EAHE for the numerical simulations.*

144 The pipe is buried to a depth of 83 cm. Its outer diameter is 20 cm and its inner diameter is 17  
 145 cm. To ensure a full developed turbulent flow inside the pipe [22], an air velocity of 4.0 m.s<sup>-1</sup>  
 146 was used for the study. The lengths of the studied EAHE systems are 20 m, 40 m or 60 m  
 147 because the length used in residential buildings is usually between 20 m and 60 m. Indeed, when  
 148 the length of the EAHE is more than 60 m, the pressure drop of air increases significantly  
 149 decreasing the COP [23]. The considered surrounding soil is the sand or bent-sand used  
 150 separately in portion No.1 and portion No.2 of the experimental EAHE (shown in Figure 2). The  
 151 dimensions and depth of each soil layer (top soil, natural soil backfill, surrounding soil and pipe

152 bedding) correspond to those of vertical section No.1 in Figure 2. The characteristics of the  
 153 different numerical simulations are summarized in Table 1. The thermal diffusivity values of  
 154 different materials are summarized in Table 2.

Simulation No.	Burial depth [m]	Air speed [m.s <sup>-1</sup> ]	Diameter of the pipe [m]	Length of the pipe [m]	Type of surrounding soil
1	0.83	4.0	0.20	20	sand
2				40	
3				60	
4				20	bent-sand
5				40	
6				60	

155 *Table 1 : Configuration parameters of different numerical simulations.*

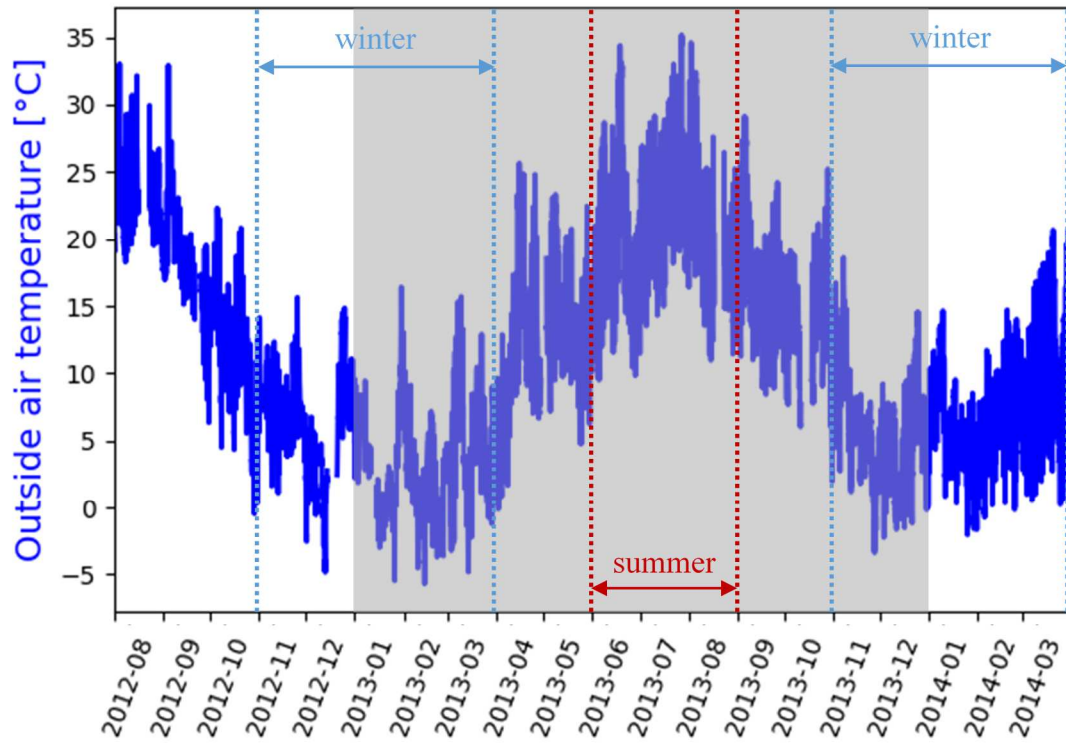
	Thermal diffusivity [mm <sup>2</sup> .s <sup>-1</sup> ]
Top soil	0.58 ± 0.06
Pipe bedding of fine sand	0.63 ± 0.08
Pipe	0.28 ± 0.01
Natural soil backfill	0.72 ± 0.04

*Table 2 : Thermal diffusivity [mm<sup>2</sup>.s<sup>-1</sup>] of different soils and materials.*

#### 156 **2.4. Applied conditions**

157 The energy performance of an EAHE depends mainly on two factors: outside air temperature and  
 158 the variation of thermal properties of the surrounding soil [18].

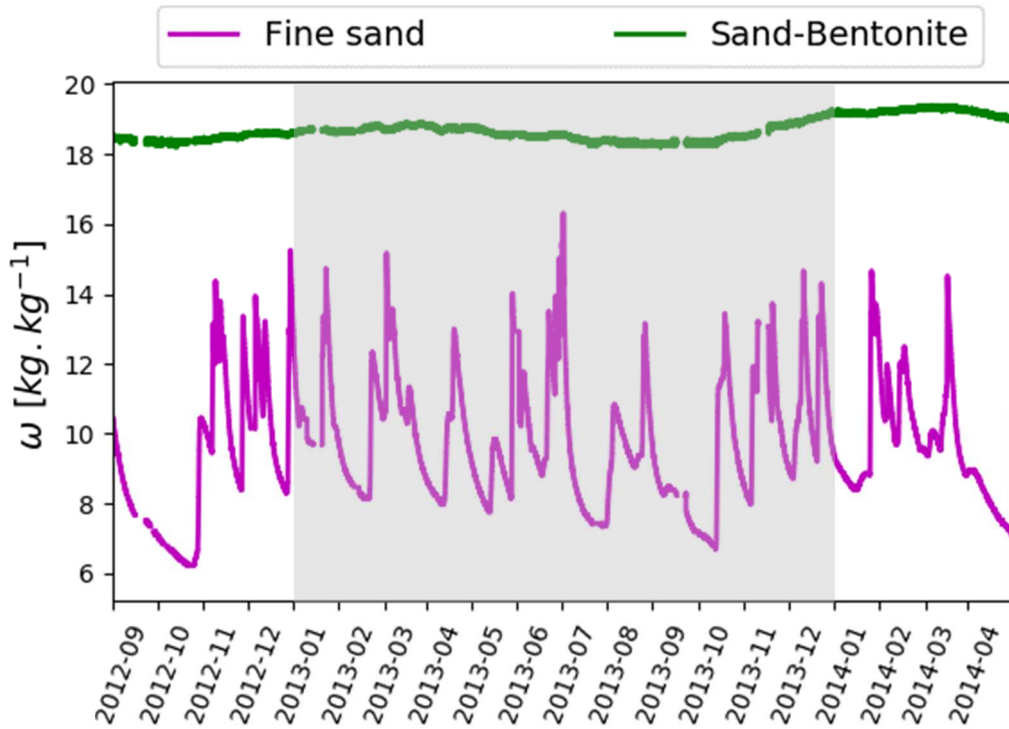
159 On the one hand, outside air temperature comes from a temperature probe placed on the surface  
 160 of the top soil. The shaded area in Figure 4 shows the outside air temperature for the year 2013,  
 161 used in the numerical simulation.



162

Figure 4 : Experimental measurement of outside air temperature. The shaded area corresponds to the period of the numerical simulation.

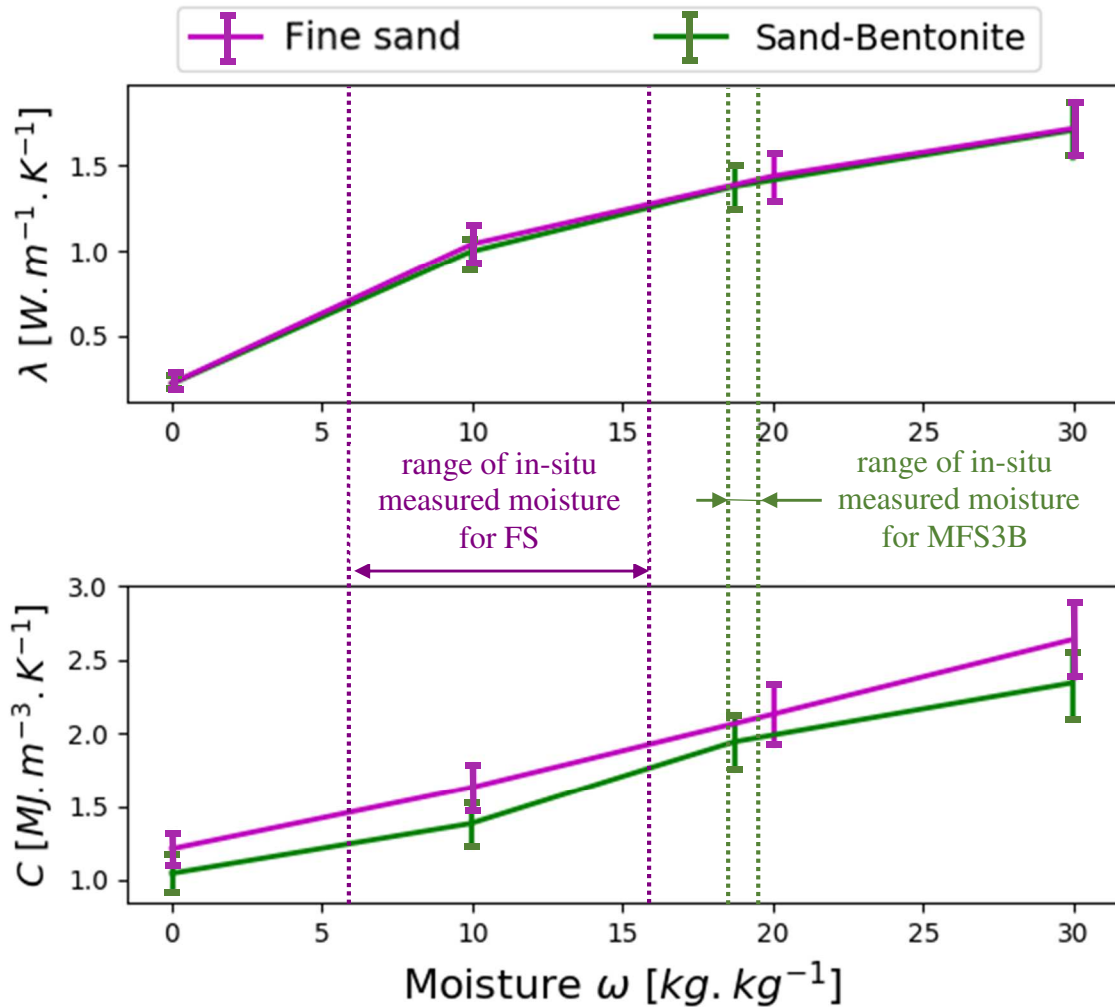
163 On the other hand, the thermal properties of the surrounding soil were obtained, indirectly, by  
 164 using the soil moisture content. It is derived from the recorded data of the relative humidity  
 165 probe for sand (portion No.1) and bent-sand (portion No.2) at the experimental EAHE site.  
 166 Figure 5 shows the experimental measurements from September 1<sup>st</sup>, 2012 to April 1<sup>st</sup>, 2014  
 167 where continuous measurements were carried out. The soil moisture varies from 6 to 16 kg.kg<sup>-1</sup>  
 168 for sand. The soil moisture of bent-sand is stable and around 19 kg.kg<sup>-1</sup>. As the outside air  
 169 temperature, the entire year 2013 (shaded area in Figure 5) was selected for the numerical  
 170 simulations.



172

Figure 5 : Experimental measurement of the soil moisture content for sand and bent-sand. The shaded area corresponds to the period of the numerical simulation.

173 To obtain the relationship between soil thermo-physical characteristics and the soil moisture con-  
 174 tent of sand and bent-sand soils, laboratory tests have been performed. A dual-probe heat-pulse  
 175 (DPHP) sensor KD2Pro® was used to carry out the measurements. Figure 6 shows the measured  
 176 results for sand and bent-sand. Between each measurement point, thermal property values are  
 177 estimated with a linear interpolation



178

Figure 6 : Experimental measurement of the thermal conductivity and volumetric heat capacity for sand (in purple) and bent-sand (in green) according to soil moisture contents.

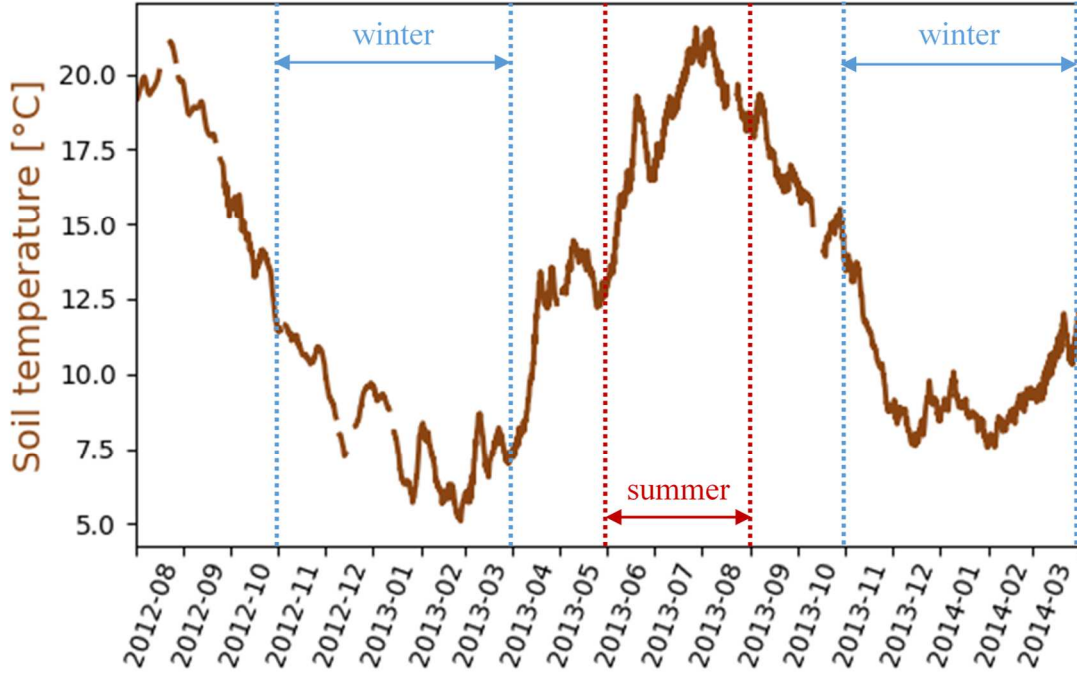
179 **3. Analysis method for numerical results**

180 Once the outlet air temperatures of the 6 studied EAHEs were simulated, different analysis  
 181 methods have been used to study energy performance and design length by comparing the results  
 182 of EAHEs with the two surrounding soils (bent-sand and sand).

183 **3.1. By-pass system**

184 Firstly, to reproduce representative condition of the EAHE systems, a by-pass system was  
 185 considered for the numerical study. This system allows the extracted air to by-pass the EAHE  
 186 when the outside air temperature is close to the soil temperature at the pipe's buried depth. In  
 187 this case, the output air temperature is equal to the outside air temperature. For example, the by-  
 188 pass system is often activated during mid-season (spring and autumn) when the use of the EAHE  
 189 is not necessary. In this study, the by-pass is activated when the outside air temperature  $T_{ext}$  is

190 between 5 °C and 26 °C. The lower temperature limit of 5 °C is defined because it is the  
 191 minimum soil temperature, measured in the geothermal platform, at the buried pipe as shown in  
 192 Figure 7. The upper temperature limit of 26 °C corresponds to the upper limit of human comfort  
 193 temperature as defined in the European directives [1].



194

*Figure 7 : Experimental measurement of the soil temperature measured in the geothermal platform at the depth of buried pipe (1.0 m).*

### 195 3.2. Analysis of energy performance

196 To compare the energy performance of the different EAHE systems, thermal exchanged power is  
 197 first studied. Under the assumption of a constant air heat capacity, thermal exchanged power  
 198 between the ground and the ventilated air through the EAHE is determined by equation (3) [21].

$$\phi(t) = v_{air} \cdot \pi \cdot r_{int}^2 \cdot C_{air} \cdot [T_{air,outlet}(t) - T_{air,intlet}(t)] \quad (3)$$

199 Secondly, energy performance is also evaluated by calculating the total exchanged energy with  
 200 the following relation (4) [17].

$$E(t_f) = \int_0^{t_f} \phi(t) dt \quad (4)$$

201 where  $t_f$  is the time duration of the simulation period. If  $E > 0$  ( $E < 0$ , respectively), it  
 202 corresponds to heating energy (cooling energy, respectively).  
 203 Finally, to highlight the energy gain by using bent-sand compared to sand, the difference of  
 204 exchanged energy  $E_{diff}$  is calculated by the relation (5).

$$E_{diff}(t_f) = E_{bent-sand}(t_f) - E_{sand}(t_f) \quad (5)$$

205 where  $E_{FS}$  is the exchanged energy of the EAHE with the sand surrounding soil and  $E_{bent-sand}$   
 206 is the exchanged energy calculated with the bent-sand surrounding soil.

### 207 3.3. Analysis of design length

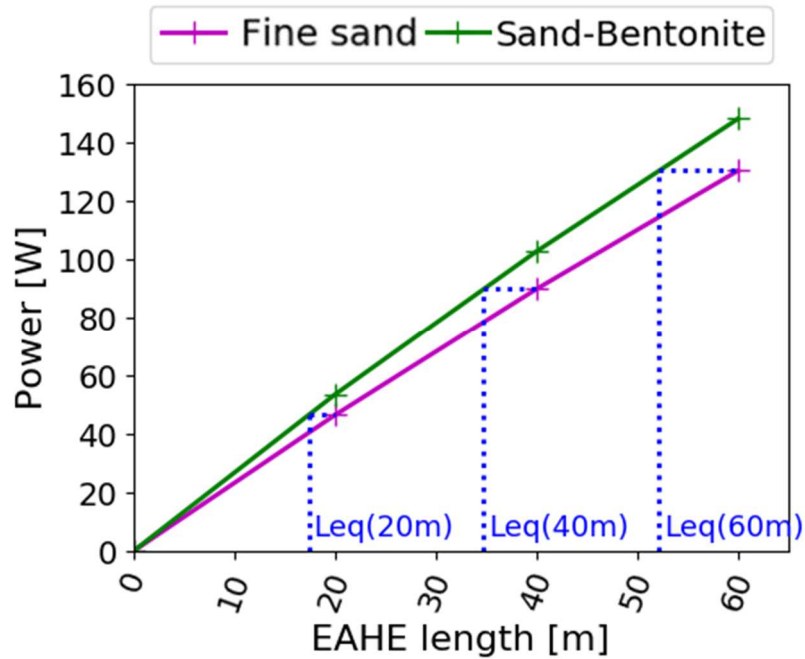
208 To analyze the impact of the improved surrounding soil at the conception phase, an eventual  
 209 reduction of the pipe's design length is studied. A new term "equivalent length" is introduced in  
 210 this study. This term is the length of an EAHE with the bent-sand surrounding soil corresponding  
 211 to the power delivered by the EAHE with a reference length (20 m, 40 m and 60 m) and with the  
 212 sand surrounding soil. Figure 8 explains how to determine the equivalent length for different  
 213 reference lengths. For example, for a reference length of  $L_{FS} = 20$  m with the sand surrounding  
 214 soil, the equivalent length is obtained by the relation (6).

$$L_{eq}(t, L_{sand} = 20 \text{ m}) = \frac{\phi_{sand}(t, L_{sand} = 20 \text{ m})}{\phi_{bent-sand}(t, L_{sand} = 20 \text{ m})} \times 20 \quad (6)$$

215 where  $L_{eq}$  is the equivalent length;  $\phi$  is the thermal exchanged power between the EAHE and  
 216 the ground with the sand surrounding soil or the bent-sand surrounding soil at the given time  $t$ .  
 217 The exchanged power per pipe length decreases along the pipe because the temperature  
 218 difference between the ground and the ventilated air decreases. Therefore, for a reference pipe  
 219 length of  $L_{sand} = 40$  m and  $L_{sand} = 60$  m, as the equivalent lengths are obtained by the  
 220 relations (7) and (8):

$$L_{eq}(t, L_{sand} = 40 \text{ m}) = \frac{[\phi_{sand}(t, L_{sand} = 40 \text{ m}) - \phi_{bent-sand}(t, L_{sand} = 20 \text{ m})]}{[\phi_{bent-sand}(t, L_{sand} = 40 \text{ m}) - \phi_{bent-sand}(t, L_{sand} = 20 \text{ m})]} \times 20 + 20 \quad (7)$$

$$L_{eq}(t, L_{sand} = 60m) = \frac{[\phi_{sand}(t, L_{sand} = 60m) - \phi_{bent-sand}(t, L_{sand} = 40m)]}{[\phi_{bent-sand}(t, L_{sand} = 60m) - \phi_{bent-sand}(t, L_{sand} = 40m)]} \times 20 + 40 \quad (8)$$



221

Figure 8 : Method to determine the equivalent length of the EAHE with an improved surrounding soil at the given time  $t$  (with real values).

## 222 4. Results and discussion

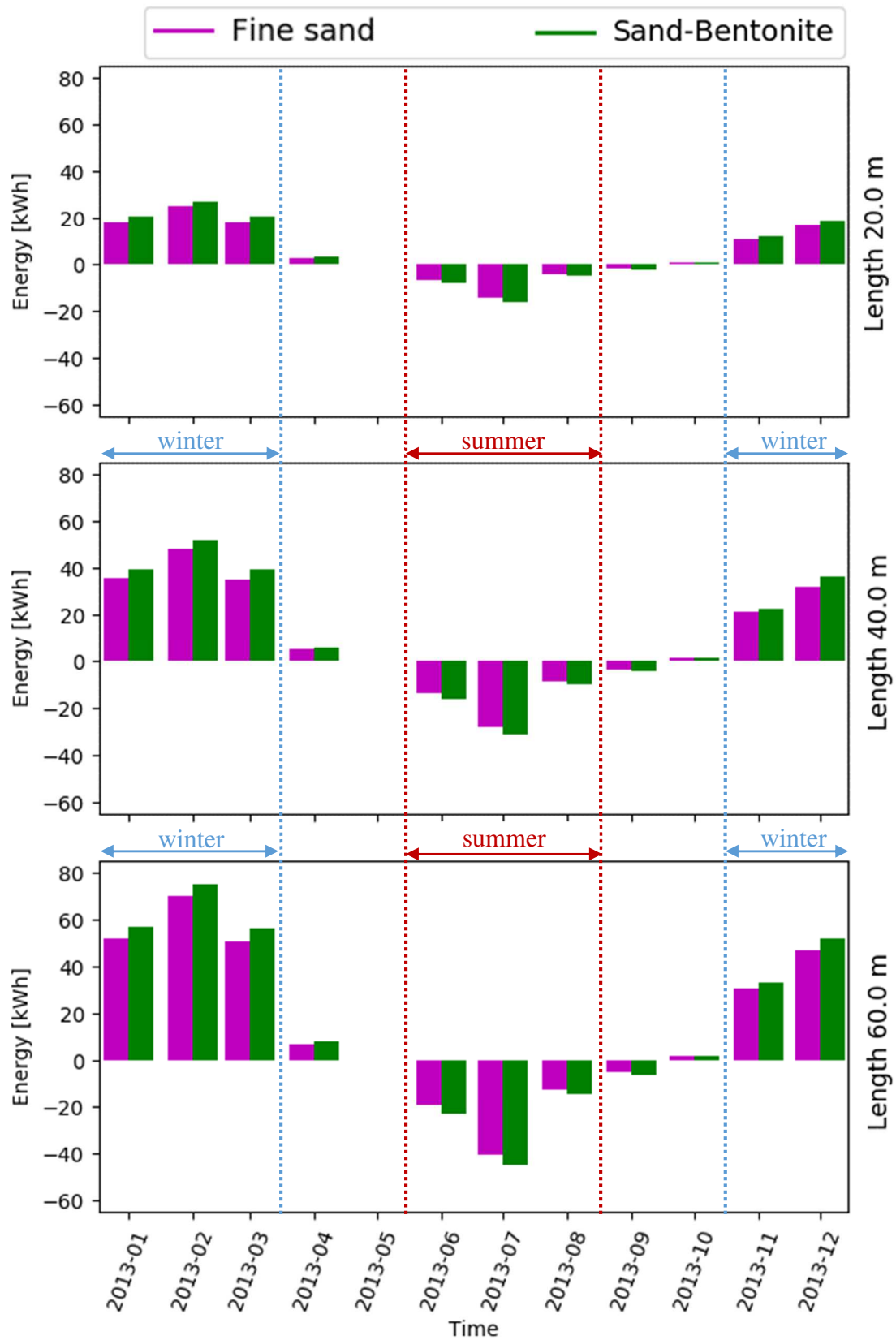
223 This part presents the analysis of the numerical simulation results. The exchanged energy for an  
 224 EAHE of different lengths (20 m, 40 m and 60 m) and the equivalent lengths are presented in  
 225 this section.

### 226 4.1. Energy performance under influence of the improved surrounding soil

227 Figure 9 shows the exchanged energy between the ground and the EAHE for the sand and the  
 228 bent-sand. Due to the by-pass system, the energy exchange is near to null during mid-season.  
 229 Apart from mid-season, two seasonal periods are of interest: the winter period for the months of  
 230 January, February, March, November and December; and the summer period for the months of  
 231 June, July and August. During these two periods, for every month of the year, the exchanged  
 232 energy is more significant with bent-sand than that with sand.

233





234

Figure 9 : Histogram of the exchanged energy between the ground and the EAHE for each month of the year and for three different numerical simulations of the pipe's length.

235 Table 3 summarizes the exchanged energies for winter and summer. Firstly, independently of the

236 surrounding soil and the seasonal period, the exchanged energy increases with the length of the

237 EAHE. For example, in winter and for sand, the exchanged energy is 88.7 kWh with a pipe  
 238 length of 20 m, it is 171.7 kWh for 40 m and 249.1 kWh for 60 m. Secondly, the exchanged  
 239 energy is greater in winter than in summer independently of the EAHE's length. The exchanged  
 240 energy can reach 273 kWh in winter and 83 kWh in summer. This is due to the climate in  
 241 Strasbourg, where winter is relatively cold while summer is not too hot. Thus, the period when  
 242 the outside air temperature  $T_{\text{ext}} < 5 \text{ }^\circ\text{C}$  is much longer than the period when  $T_{\text{ext}} > 26 \text{ }^\circ\text{C}$ . Finally,  
 243 it can be noticed that exchanged energy is greater with bent-sand than that with sand. The  
 244 average energy gain using the improved surrounding soil is approximately 12 %. The increase of  
 245 exchanged energy can reach 14.6 % for the 20 m length EAHE in summer.

Season	Pipe's length [m]	Exchanged energy [kWh]		Energy gain [%]
		Sand	Bent-sand	
Summer (June - August)	20	-26.1	-29.9	14.6
	40	-50.3	-57.4	14.1
	60	-72.8	-82.5	13.3
Winter (Jannuray to March and November to December)	20	88.7	98.4	10.9
	40	171.7	189.2	10.2
	60	249.1	273.1	9.6

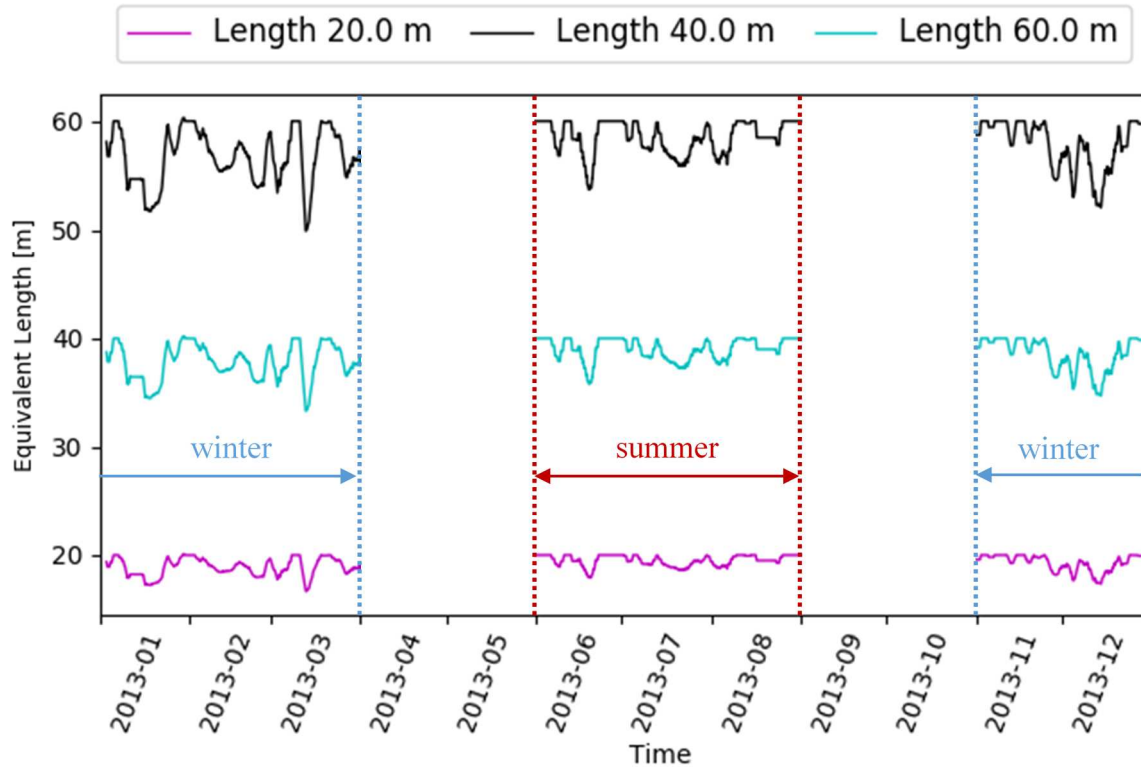
Table 3 : Simulated Exchanged energies for different EAHE configurations.

#### 246 4.2. Design length under influence of the improved surrounding soil

247 In the previous section, the results of the numerical simulations show that the bent-sand  
 248 surrounding soil improves, significantly, the energy performance of an EAHE. Consequently, for  
 249 an EAHE with a sand surrounding soil designed for a defined energy requirement of buildings,  
 250 the use of a bent-sand surrounding soil would shorten the length of the exchanger pipe.

251 Figure 10 represents the equivalent length of the EAHE systems with the improved surrounding  
 252 soil (with bent-sand) corresponding to the reference EAHE systems with the sand surrounding  
 253 soil. The results are presented for the three reference lengths: 20 m, 40 m and 60 m during the

254 entire year, 2013. During mid-season when the by-pass system is activated, no comparison can  
 255 be performed. Thus equivalent length remains equal to the reference length (with the sand  
 256 surrounding soil). Reduction of the pipe's length can be observed for winter and summer  
 257 periods.



258

Figure 10 : Graphic representation of the equivalent length for the three EAHE lengths.

259 Table 3 summarizes the average equivalent lengths. For the reference length of 60 m, the pipe's  
 260 length with the bent-sand surrounding soil decreases by 7.9 m [13.2 %] for the summer period,  
 261 5.5 m [9.8 %] for the period winter and 5.9 m [9.8 %] for the entire year. This tendency is similar  
 262 for others reference lengths (40 m and 60 m). In general, the pipe's length can be reduced by  
 263 about 10 % for the entire year. This reduction is greater during summer (about 13 %) than that in  
 264 winter (about 9 %).

EAHE length with sand	Equivalent length $L_{eq}$ [reduction percentage]		
	Summer	Winter	The entire year
20.0 m	17.4 m [-13.0 %]	18.1 m [-9.5 %]	18.0 m [-10.0 %]
40.0 m	34.7 m [-13.3 %]	36.3 m [-9.3 %]	36.0 m [-10.0 %]
60.0 m	52.1 m [-13.2 %]	54.5 m [-9.2 %]	54.1 m [-9.8 %]

Table 3 : Summary of the equivalent length for three EAHE lengths and for three periods: summer, winter and the entire year.

265 **4.3. Further discussions**

266 The results of the numerical simulations reveal two important aspects: the gains from both  
267 energy performance and design length by using a bent-sand surrounding soil in EAHE systems.  
268 This influence comes from its stable high soil moisture content. The thermo-physical properties  
269 of sand and bent-sand are similar, as shown in Figure 6. However, the addition of bentonite (3 %)   
270 in sand allows capturing and storing of large amount of water in the soil. Therefore, the soil  
271 moisture content of the improved surrounding soil has been experimentally shown to be stable  
272 and high during the entire year (see Figure 5), which stabilizes, significantly, the heat exchange  
273 between the EAHE and the ground and increases it definitely by approximately 12 % for a very  
274 low initial cost.

275 **5. Conclusions**

276 A numerical model is used to simulate 6 EAHE systems over the entire year for three different  
277 lengths (20 m, 40 m and 60 m) and two types of surrounding soil (sand and bent-sand). It is  
278 shown that the addition of a small part of bentonite (3 % in the studied cases) in the sand sur-  
279 rounding soil can stabilize, significantly, heat exchange and improve energy performance by  
280 about 12 %. Moreover, to design an EAHE with a defined power, the use of the bent-sand sur-  
281 rounding soil can lead to a reduction of the EAHE's length. This reduction is about 13 % in  
282 summer, 9 % in winter and 10 % over the entire year.

283 A further economic study with various costs is to be carried out to calculate real economic gains  
284 of using bentonite-sand mixture. Different percentages of bentonite-sand are also be taken into  
285 consideration to determine the optimal proportion to apply in the surrounding soil.

286 **ACKNOWLEDGES**

287 This work is funded by the European Commission Initiative INTERREG IV, Upper Rhine  
288 Programme (Project B20-TEM3). The authors thank D. Schwartz for providing language help.  
289 Moreover, the authors are grateful of the contributions of the editorial board and the reviewers.

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