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### ► To cite this version:

Shengshi Dong, Xiaozhao Li, Anh Minh A.M. Tang, Jean-Michel Pereira, van Tri Nguyen, et al.. Thermo-mechanical behavior of energy diaphragm wall: Physical and numerical modelling. Applied Thermal Engineering, 2019, 146, pp.243-251. 10.1016/j.applthermaleng.2018.09.054 . hal-02877008v1

**HAL Id: hal-02877008**

**<https://hal.science/hal-02877008v1>**

Submitted on 21 Jun 2020 (v1), last revised 23 Jun 2020 (v2)

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1 **Thermo-mechanical behavior of energy diaphragm wall: physical**  
2 **and numerical modelling**

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20 **Abstract:** The paper presents a study of the thermo-mechanical behavior of energy diaphragm  
21 wall. A physical model, which consists of a small-scale concrete diaphragm wall equipped with a  
22 heating exchange pipe, was used. A heating test was performed where hot water (at 50 °C) was  
23 circulated through a heat exchange pipe for 75 h. The results show that the temperatures in the  
24 wall and in the soil increased quickly during the first 20 h and reached stabilization at the end of  
25 the experiment. Heating induced increase of axial strain in the wall and earth pressure at the  
26 soil/wall interface. In addition to the experiment, a numerical model, using finite element analysis,  
27 was used to predict the behavior of the wall during this experiment. The good agreement between  
28 the numerical and the experimental results allows the main phenomena that took place to be  
29 explained; heating induces thermal expansion of the wall that results in the modification in stress  
30 in the wall and at the soil/wall interface. In addition, since the pipe was located closer to one side  
31 of the wall, the thermal expansion of the wall was not homogenous, and the wall bent during  
32 heating.

33 **Keywords:** Thermo-mechanical behavior; Energy diaphragm wall; Physical model; Numerical  
34 simulation

35

## 36 **1. Introduction**

37 A thermo-active (or energy) geostructure is a new-style Ground Source Heat Pump (GHSP) system  
38 that consists of conventional geostructures (*e.g.* pile foundation, tunnel lining, diaphragm wall)  
39 with individual or several pipe circuits (high-density polyethylene pipes, HDPE) of primary circuit  
40 embedded within to enable heat exchange with the surrounding ground [1]. In winter, heat is  
41 extracted from the ground for the purpose of heating and in summer, heat is injected into the  
42 ground to provide cooling. Energy geostructures are considered an interesting and promising  
43 technology to tackle the increasing energy demands for heating and cooling of buildings and other  
44 infrastructures, by making use of it as a local and sustainable source. However, there are still  
45 concerns about the thermal exchange, between the structure and the ground, which may induce  
46 variation in the stress/strain behavior of the geostructure and, as a consequence, be a threat to its  
47 safety and performance. Thus, several research works have been focused on the thermo-  
48 mechanical behavior of energy geostructures in order to better understand its stress/strain behavior  
49 under combined thermal and mechanical loading [2-8].

50

51 However, most of the existing studies are related to the thermo-mechanical behavior of energy  
52 piles. The methods used include in situ experiments [9-12], laboratory tests [13-23] and numerical  
53 simulations [24-29]. It has been reported that there are significant changes in stress distribution  
54 and shaft resistance due to constraints on the thermal expansion/contraction [30]. Although these  
55 phenomena are not expected to lead to detrimental consequences, they should be taken into  
56 consideration at the design stage.

57

58 Few studies of the thermo-mechanical performance of energy diaphragm walls have been  
59 published however [31, 32]. It has been suggested that thermally-induced strains and stresses also  
60 develop in energy walls [32]. However, their effects are less predictable than in energy piles  
61 because of their greater complexity in terms of geometry. Sterpi *et al.* [32] performed 3D thermo-  
62 mechanical Finite Element Analyses (FEA) and concluded that the thermally induced effects on  
63 the structure were not negligible and could be observed partly as additional displacements, partly  
64 as variations of the internal actions. Bourne-Webb *et al.* [31] also performed numerical  
65 simulations and found that changes to the wall mechanical response were dominated by seasonal  
66 temperature changes.

67

68 The most important function of the diaphragm wall is for ground support and seepage control. If  
69 there is crack in the wall, the deformation caused by thermal expansion/contraction and lateral  
70 soil pressure may aggravate the damage. Some diaphragm walls are also applied for bearing  
71 purpose, as a result, the thermally-induced strains and stresses are thus important to be investigated.  
72 Numerical analysis have demonstrated an increase of radial contact pressures on the soil-pile  
73 interface due to temperature-induced expansion of the pile [33, 34]. For energy pile, this increase  
74 of radial contact pressures could only increase the soil-pile frictional resistance. But for diaphragm  
75 wall, due to the existence of excavation at one side of the wall, the pressure change may cause  
76 additional deformation after Sterpi *et al.* [32]. However, the bending moment caused by heating  
77 was small and overwhelmed by the effect of environmental thermal boundary conditions through

78 numerical analysis by Bourne-Webb *et al.* [31].

79

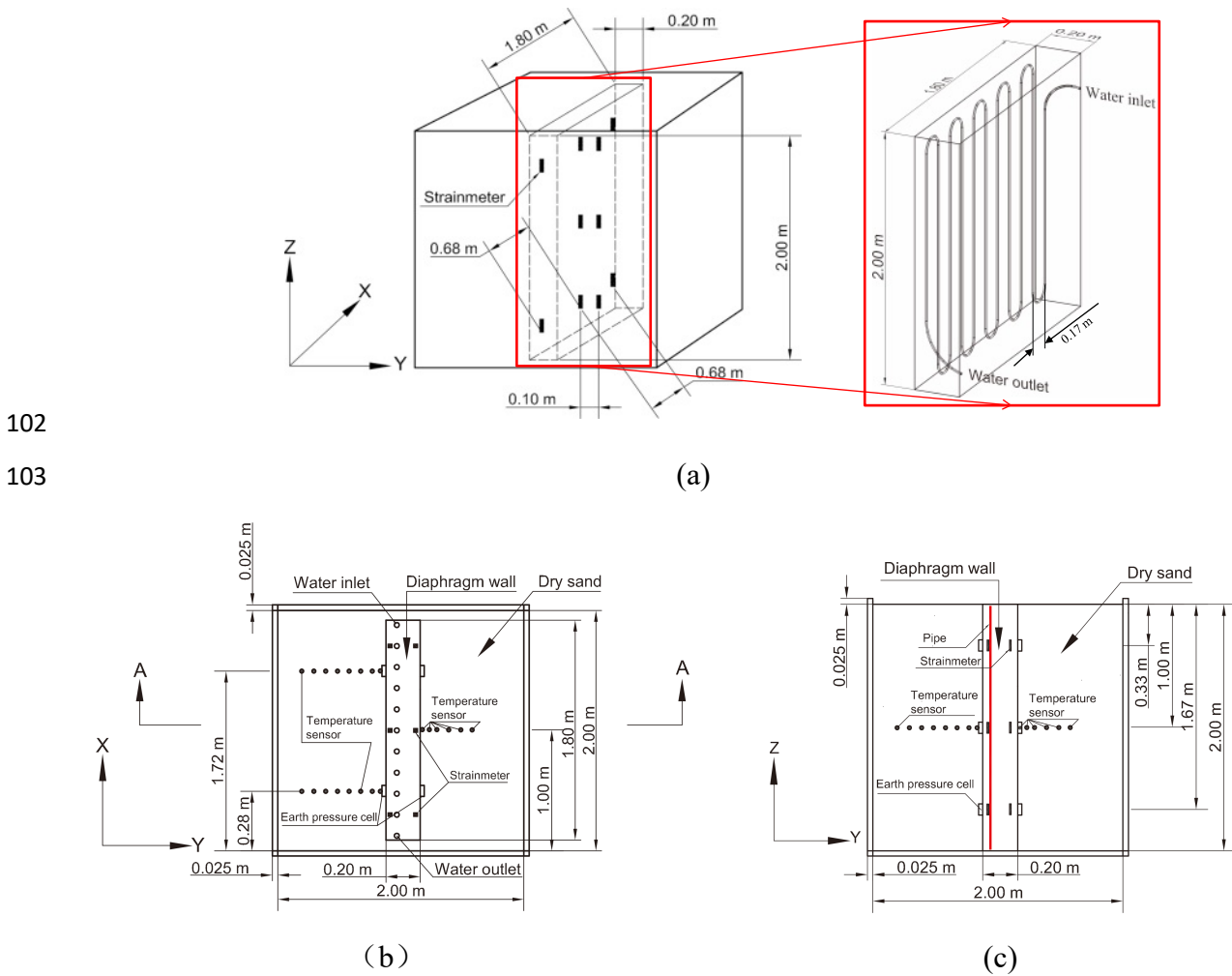
80 This paper presents a study to evaluate the thermo-mechanical response of an energy diaphragm  
81 wall by using physical and numerical modeling. A small-scale energy diaphragm wall was  
82 installed in dry sand. Its behavior under thermal loading was monitored using strain, stress and  
83 temperature sensors embedded inside/on the wall and also in the surrounding soil. At the same  
84 time, its behavior was predicted by using Finite Element Analyses (FEA). The combination of the  
85 two methods allows better understanding the thermo-mechanical behavior of an energy diaphragm  
86 wall when its temperature is varied.

87

## 88 **2. Physical model**

89 The schematic view of the physical model is shown in Figure 1. A small-scale concrete diaphragm  
90 wall (2.00 m high, 1.80 m wide, and 0.20 m thick) was installed inside a steel box and the bottom  
91 of the wall was in contact with the bottom of the box. The internal height and width of the box are  
92 similar to those of the wall. The thickness of the box walls and floor is 25 mm with other 30 mm  
93 grillage structure outside, which is large enough to consider that the box is rigid. The box was  
94 exposed to the indoor air with a controlled temperature of  $10 \pm 2^\circ\text{C}$  and the heat convection  
95 between the surfaces and air is natural convection. Prior to the experiment, the box was filled with  
96 dry sand in layers of 0.2-m thickness which were compacted to a density of about  $1.62 \text{ Mg/m}^3$   
97 (corresponding to a relative density of 80% and void ratio of 0.63). The control of density by layer  
98 ensures its uniformity throughout the test specimen. This physical model can be considered

99 representative of the wall below the internal excavation level. As a result, the effect of the thermal  
 100 boundary conditions on the thermo-mechanical behavior, identified in other studies [30, 31], will  
 101 not be captured.



104 Fig. 1. Schematic view of the experimental setup; (a) 3D view of the physical model with the  
 105 details of the pipe and strainmeters; (b) Horizontal section at  $Z = 1.00$  m; (c) Section A-A, Vertical  
 106 section at  $X = 1.00$  m.

107  
 108 The soil temperature was measured at various locations located on a plane at 1-m depth (see Figure

109 1c). At this depth, the temperature sensors were distributed in three lines, two on the left-hand side  
110 and one on the right-hand side (see Figure 1b). This allows the soil temperature to be measured at  
111 different distances from the diaphragm wall surfaces at the same depth. The diaphragm wall was  
112 equipped with high-density polyethylene pipes (10 mm in external diameter and 8 mm in internal  
113 diameter) to distribute the heating fluid, and various sensors to measure earth pressure,  
114 temperature and strain. The details are shown in Figures 1. The pipes were distributed on a plan  
115 located at 0.05 m from the left-hand side surface of the wall and the distance between the pipes  
116 was 0.17 m (see Figure 1b, c). The details of the pipe arrangement are shown in Figure 1a. To  
117 measure the earth pressure at the soil/wall interface, 12 sensors were used. These sensors were  
118 distributed at three depths (0.33 m, 1.00 m, and 1.67 m) (see Figure 1c). At each depth, two sensors  
119 were located on each side of the wall (see Figure 1b). Several strainmeters were tied to the rebars,  
120 as shown in Figure 1a, to measure the strain at various locations inside the wall. Note that the  
121 strainmeters and the earth pressure transducers have integrated with thermistors to measure the  
122 temperature. The characteristics of the sensors used are shown in Table 1 and the calibration and  
123 correction for the temperature were done by the producers and considered in the data processing.  
124 The wall was fabricated outside of the box. After 30 days of curing, it was then installed inside  
125 the box and the earth pressure and soil temperature sensors were installed during the compaction  
126 of dry sand to fill the box.

127

128 Table 1. Detailed information of sensors

Sensor	Market model No.	Specification	Capacity	Sensibility	Error
--------	------------------	---------------	----------	-------------	-------



Earth pressure cell	JTM-V2000	Vibrating wire	300 kPa	$\leq 0.24$ kPa	$\leq 1$ kPa
Strainmeter (embedment)	BGK-4200	Vibrating wire	3000 $\mu\epsilon$	1 $\mu\epsilon$	$\leq 3$ $\mu\epsilon$
Temperature sensor	Pt100	Thermal resistance	0-300 °C	$\leq 0.04\%$	0.3 °C

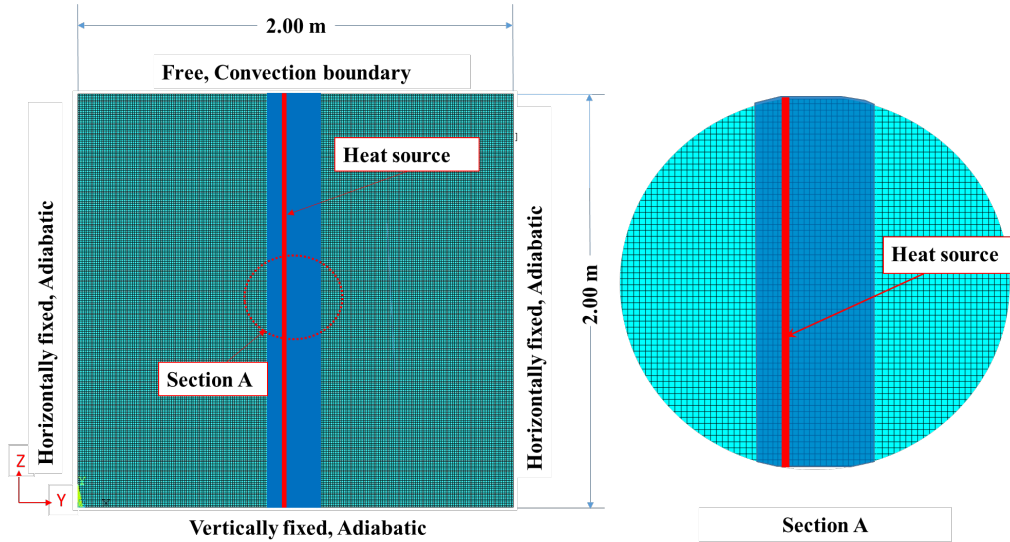
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130 After the installation of the experiment, heating was applied to the wall by circulating water  
 131 through the pipes at a temperature of 50 °C and with a flow rate of 0.03 m<sup>3</sup>/h for a period of 75 h.  
 132 Beside the temperature evolution which was measured at various locations inside the wall and in  
 133 the soil, earth pressures at the soil/wall interface and strains inside the wall were also recorded.

### 134 **3. Numerical model**

135 In order to predict the mechanical behavior of the wall during this experiment, Finite Element  
 136 Analysis (FEA) (using ANSYS) was under taken. The 2D mesh, plotted in Figure 2, represents  
 137 the section shown in Figure 1c. Plane strain conditions were applied corresponding to the  
 138 boundary conditions of the experiment. The horizontal displacements at the left-hand side and the  
 139 right-hand side were restrained. The vertical displacement at the bottom of the mesh was also  
 140 restrained while the stress applied to the top of the mesh was null. The downward vertical  
 141 displacement of the base of the wall was restrained but the horizontal displacement was not.  
 142 According to the experimental results, the thermal boundary conditions on the left-hand side and  
 143 right-hand side have only small influence on the temperature distribution. For this reason, the  
 144 thermal boundary conditions on these two sides were supposed to be adiabatic. Heat flux was  
 145 equally supposed to be negligible at the bottom boundary. On the top of the model, thermal

146 convection boundary was set with an air temperature of 10 °C and a convective heat transfer  
147 coefficient of 2.5 W/(m<sup>2</sup>.K)([31]), as it was open to the air.



148  
149 Fig.2 Finite element mesh and boundaries conditions used for the numerical simulations.

150  
151 The governing laws used in this study are summarized as follows: (i) only conduction was  
152 considered for heat transfer; (ii) the mechanical behavior of the wall was linear elastic while that  
153 of the soil was elasto-plastic with the Drucker-Prager yield criterion; (iii) the thermo-mechanical  
154 behavior of the wall and soil was linear elastic. The material parameters used for the simulation  
155 are shown in the Table 2. Among the parameters, the density, thermal conductivity and specific  
156 heat of cement mortar and sand used in the FEA were measured by specialized equipment and  
157 also calibrated by one dimensional finite difference method with MATLAB. The Young's  
158 modulus and Poisson's ratio of cement mortar were measured by elastic modulus test machine.  
159 Other parameters of cement mortar and sand were taken from the literatures ([35-37]). It should

160 be stated that the coefficient of linear expansion was chosen at  $0.6 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$  from literature [35],  
 161 which gives a typical linear thermal expansion coefficient for dense quartzose sands from  $0.6 \times 10^{-5}$   
 162  $^\circ\text{C}^{-1}$  to  $2.0 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$ . The lowest value was chosen to examine the effects of soil thermal  
 163 expansion on the thermal-mechanical behavior of the wall. For the friction angle, there are  
 164 literatures which give  $30\text{-}36^\circ$  from loose sand to dense sand [36, 38], we chose  $30^\circ$  as it's density  
 165 may not easy to compacted to the design stage of the lower depth. According to literature review  
 166 [36], the dilation angle of dense sand and loose sand are from  $0\text{-}12^\circ$  and  $0\text{-}10^\circ$ , respectively. It  
 167 was chosen at  $4^\circ$  as an intermediate value in the present study.

168

169 Table 2. Materials parameters used for simulation

Parameter	Cement mortar	Dry sand
Thermal conductivity (W/(m.K))	1.20	0.32
Density (Mg/m <sup>3</sup> )	1.55	1.62
Specific heat (J/(kg.K))	736	700
Young's modulus (MPa)	12,000	50
Poisson's ratio (-)	0.20	0.23
Coefficient of linear expansion ( $\mu\epsilon/^\circ\text{C}$ )	10	6
Cohesion (kPa)	—	0.1
Friction angle ( $^\circ$ )	—	30
Dilation angle ( $^\circ$ )	—	4

170

171 In order to simulate the heating phase performed in the experiment, the temperature of the pipes  
172 (the vertical line located inside the wall, see Figure 2) was imposed. The initial temperature of  
173 the whole system was first fixed at 10 °C (following the experimental observation). To start the  
174 heating phase, the temperature of the pipe was increased from 10 °C to 48.5 °C following  
175 function (1):

$$176 \quad T = \frac{2.07 \bullet t + 1.1615}{0.0414 \bullet t + 0.12323} \quad (1)$$

177 where  $t$  is elapsed time and  $T$  is temperature. This choice allows fitting the experimental data of  
178 the temperature measured by the sensor that is closest to the pipes (0.03 m from the pipe axis, on  
179 the left-hand side).

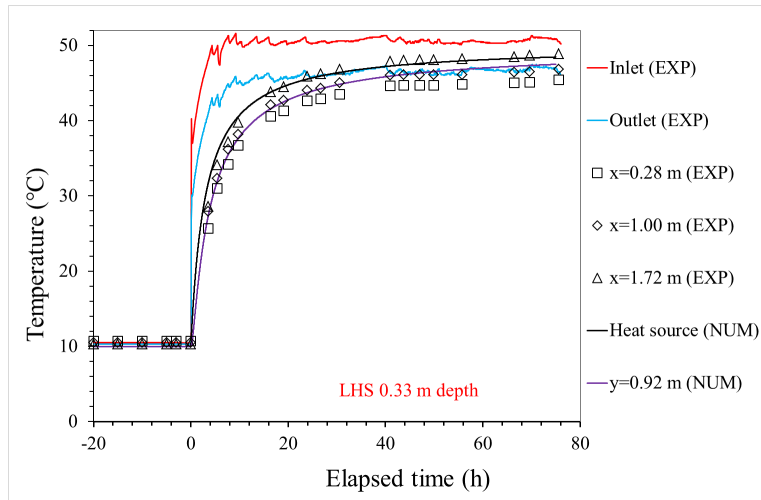
#### 180 **4. Result**

181 In this section, the results obtained from physical test and numerical analysis are compared in the  
182 same figures.

183 Figure 3 shows the temperature measured within the wall on the left-hand side in the plane of the  
184 wall panel at three different depths (0.33 m, 1.00 m and 1.67 m) and on the right-hand side at mid-  
185 plane ( $x = 1.00$  m Fig.1) versus elapsed time (the origin corresponds to the start of the heating  
186 phase). The symbols represent the experimental data (EXP) and the continuous lines represent the  
187 numerical results (NUM). Note that in the experiments, more than one sensor exists for one  
188 distance (see Figure 1b). As an example, at  $y=0.92$  m on the left-hand side (Figure 3) within the  
189 wall, there are three sensors on each depth (0.33 m and 1.67 m). The results obtained by these  
190 three sensors (showing an increase of temperature from 10 °C to 45 °C) have a difference of about

191 3-4 °C at the end of the heating phase. This difference can be explained by the gradual cooling of  
192 the fluid while circulating into the pipe which represents an ordinary characteristic condition of  
193 energy diaphragm wall.

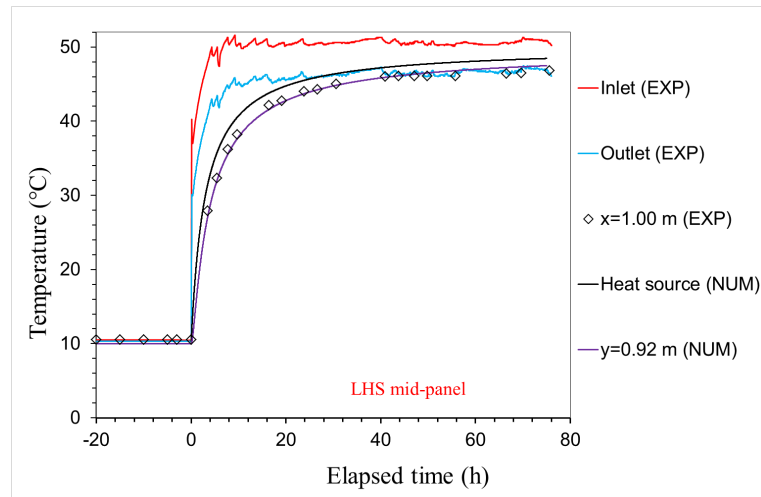
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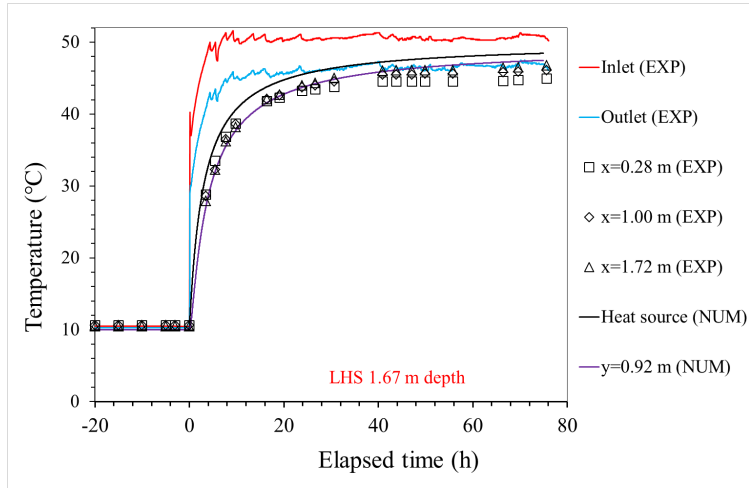
(a)



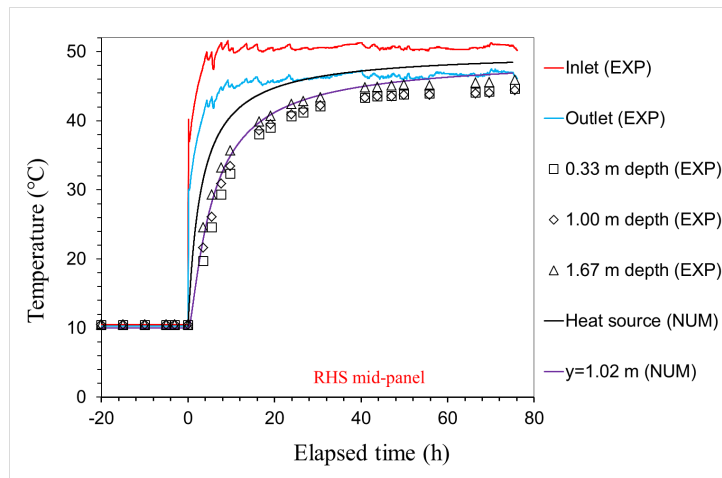
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(b)



(c)



(d)

199  
200

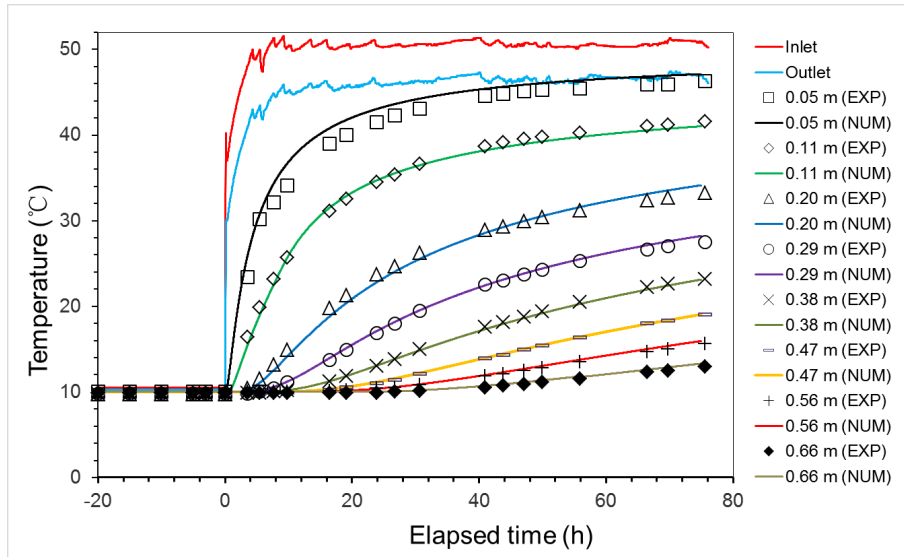
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202

203 Fig.3. Temperature versus elapsed time within the wall on the left-hand side along the x  
204 coordinate at depth of (a) 0.33 m and (b) 1.00 m and (c) 1.67 m and on the right-hand side at  
205  $x=1.00$  m for various depths (d)

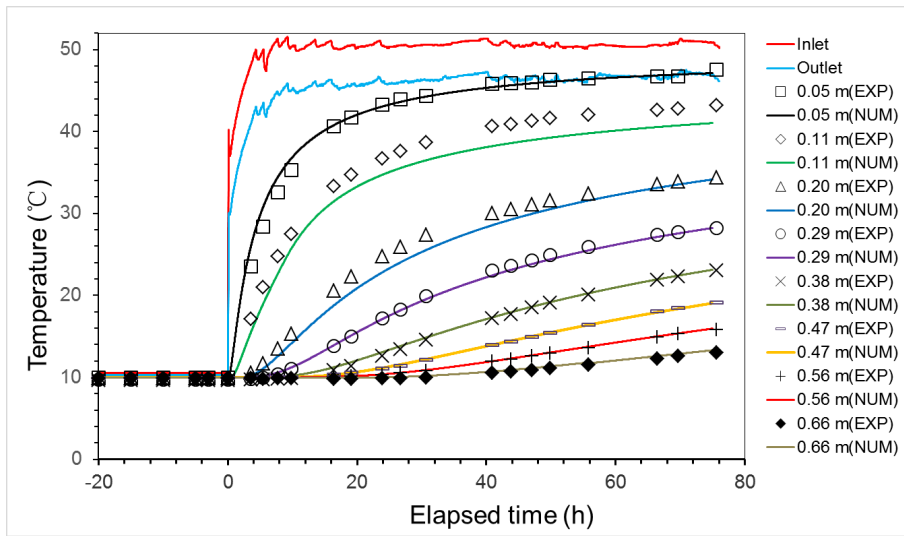
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207 Figure 4 shows the temperature for each single line of sensors embedded in the sand. The  
208 agreement between the experimental data and the numerical results confirms that the numerical  
209 2D finite element model is suitable to predict the heat transfer in sand in this experiment.

210



(a)



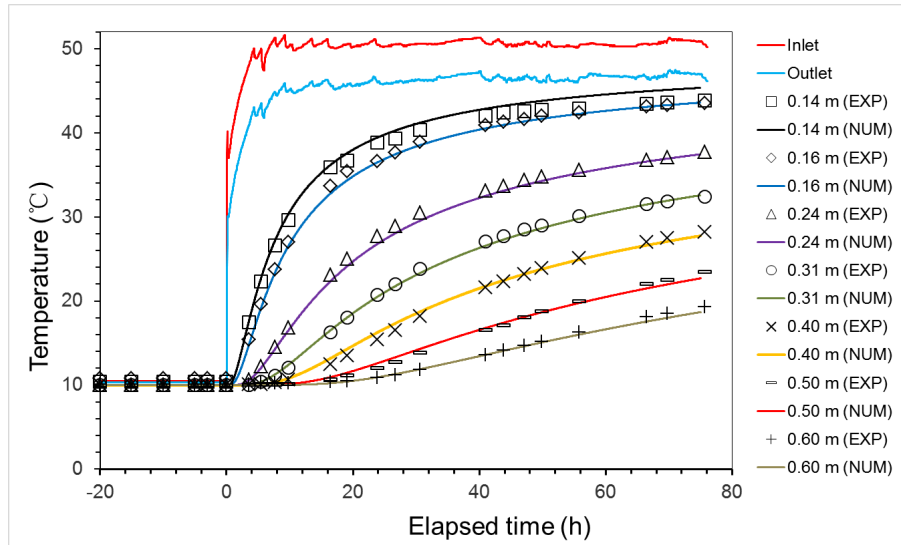
(b)

211

212

213

214



(c)

215

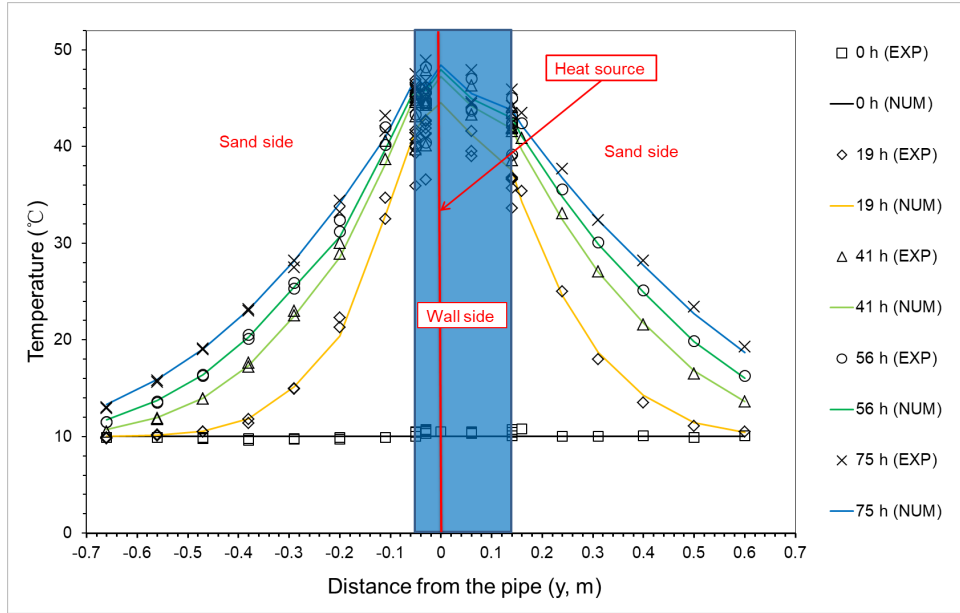
216

217 Fig.4. Temperature versus elapsed time in the sand mass at various distances from the pipes  
 218 axis: (a) on the left-hand side at  $x = 0.44$  m; (b) on the left hand side at  $x = 1.56$  m; (c) and on  
 219 the right-hand side at  $x = 1.00$  m.

220

221 Figure 5 shows the temperature profile measured at various moments. It can be seen that at a given  
 222 time, the temperature at a location closer to the pipe is higher. This plot allows two zones to be  
 223 distinguished: inside the wall, the temperature gradient is smaller than in the soil. That can be  
 224 explained by the thermal conductivities of these materials and the boundary conditions: the wall,  
 225 made of cement, is more conductive than the sand and therefore, the temperature gradient is then  
 226 smaller.





227

228 Fig.5 Temperature versus distance from the pipe at various elapsed times in the middle of the  
 229 panel ( $z=1.00$  m)

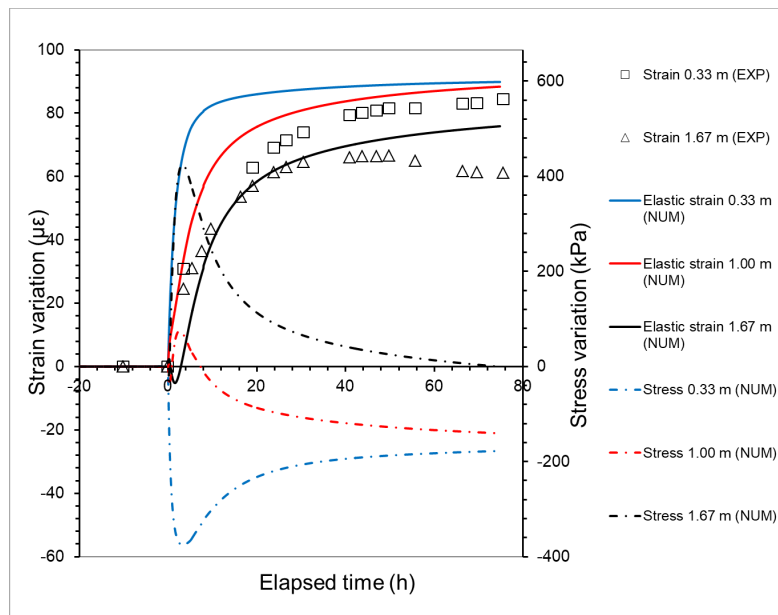
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231 The numerical results shown in Figures 3, 4 and 5 are in good agreement with the experimental  
 232 results. That confirms, in this experiment, heat transfer is mainly governed by heat conduction (as  
 233 considered in the numerical simulation). This agreement confirms also that the thermal boundary  
 234 conditions used in the simulation are acceptable. In addition, as a 2D mesh was used in the  
 235 simulation, the numerical results should be compared with the mean values obtained in the  
 236 experiments with various sensors located at the same distance. The non-uniform of the  
 237 temperature distribution along the X direction (observed from the experiments) can be ignored in  
 238 the numerical model.

239

240 Figure 6 shows the vertical strain (Z direction, see Figure 1a) measured at various x coordinates  
 241 by the strainmeters. Note that all the strainmeters on the left-hand side (Figure 6a, 6b and 6c) are  
 242 located 0.03 m from the pipe. The results show similar trends for all sensors; a rapid increase of  
 243 strain during the first 20 h (corresponding to the increase of fluid temperature during the  
 244 experiment) followed by a more stable phase. The final strain is in the range of 50-70  $\mu\epsilon$  (except  
 245 one sensor at 0.33-m depth). The three sensors located at 0.33-m depth show larger strain variation  
 246 than those at 1.67-m depth; there is only one sensor located at 1.00-m depth. On the right-hand  
 247 side (Figure 6d), only one sensor was used for each depth. Note that these sensors are located 0.06  
 248 m to the right-hand side of the pipes. The results obtained by these sensors are quite similar  
 249 showing a quick increase during the first 20 h and stabilization at 55 - 65  $\mu\epsilon$ . These discrepancies  
 250 in strains can be directly linked to the heterogeneity of temperature distribution of the wall shown  
 251 in Figure 6.

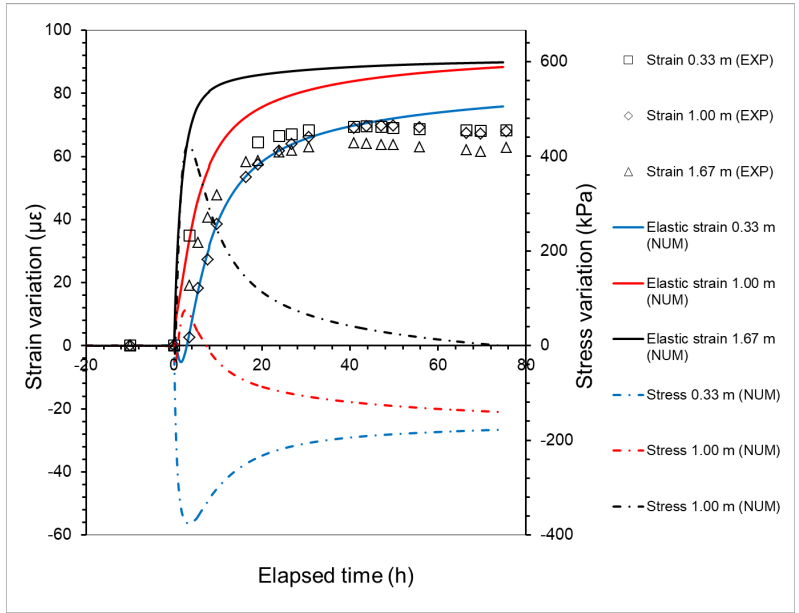
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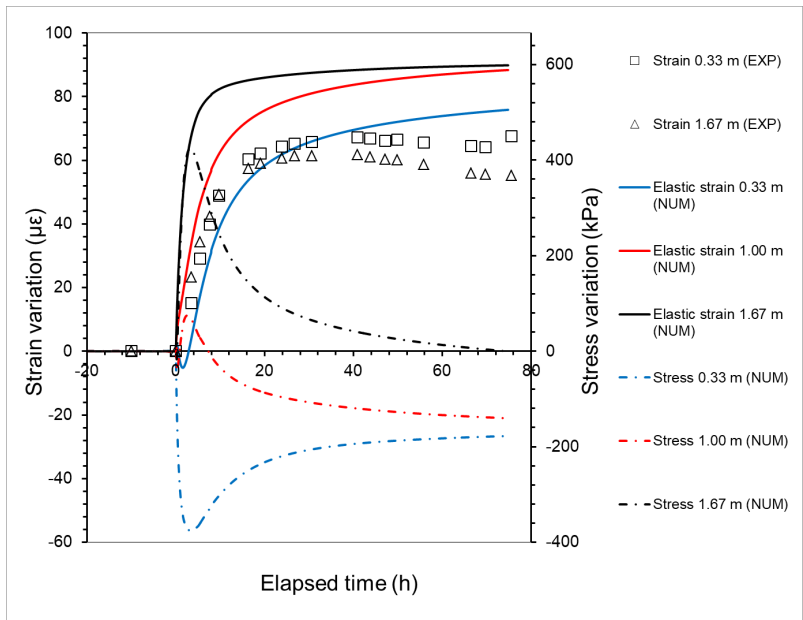
(a)



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256

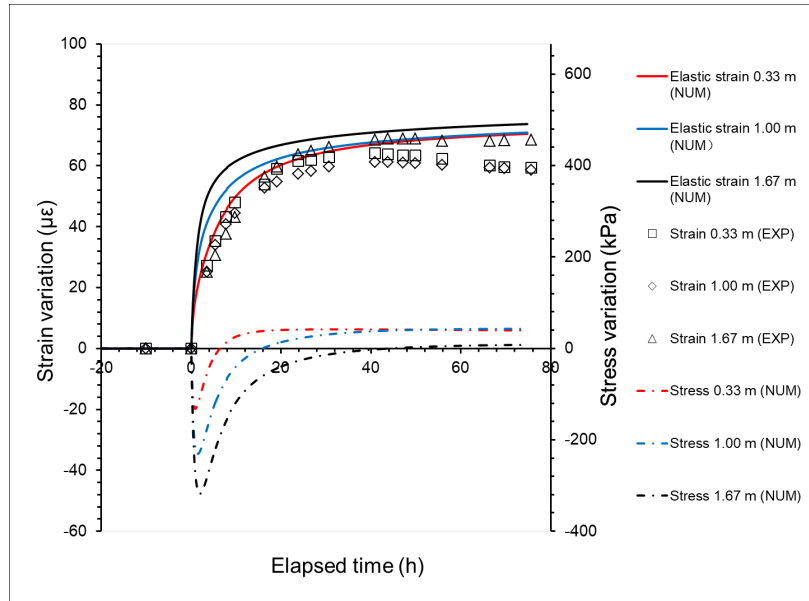
(b)



257

258

(c)



(d)

259

260

261 Fig.6. Vertical strain and stress versus elapsed time on the left-hand side at (a)  $x=0.28$  m ; (b)  $x$

262 = 1.00 m ; (c)  $x=1.72$  m ; (d) and on the right hand at  $x=1.00$  m.

263

264

265 The vertical strains predicted by the numerical analysis are also shown in the Figure 6 (positive

266 strain corresponds to expansion). On the left-hand side, the numerical analysis show that heating

267 induced a quick expansion at 0.33-m depth followed by stabilization at  $80 \mu\epsilon$ . This result is similar

268 to that obtained by the experiment. However, for the other depth (1.67 m), the numerical analysis

269 shows a contraction during the first hours. This contraction was then followed by expansion and

270 the final values are also similar to the experimental ones. The trend of the vertical strains on the

271 right-hand side shows a good agreement between the numerical and the experimental results.

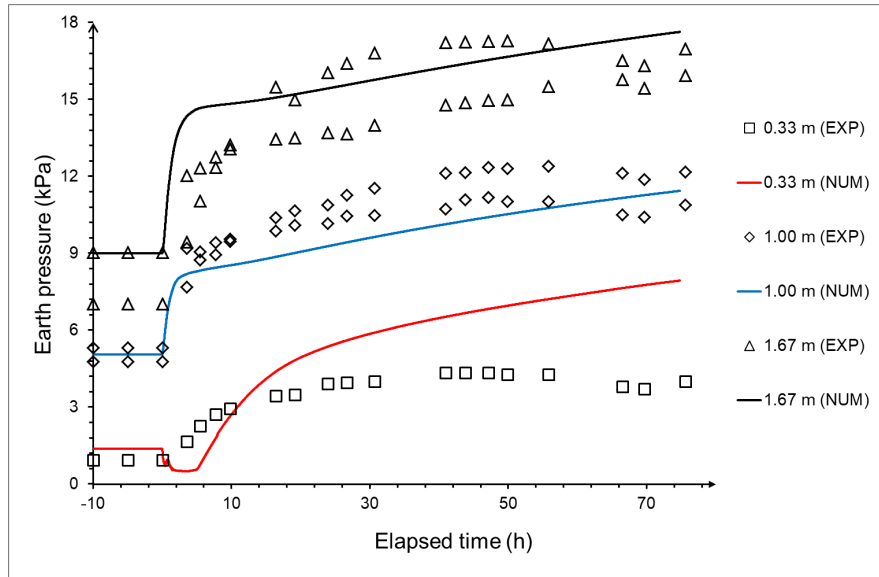
272

273 The following mechanisms can be mentioned to explain these results (see also the vertical stress  
274 variation plotted in the Figure 6). The high value of vertical stress is related to the temperature  
275 gradient in the wall thickness (see Figure 1). When the temperature of the wall increases, the  
276 vertical strain increases by the thermal expansion. As the boundary condition at base of the domain  
277 was vertically fixed, the deformation of the wall could only expand upward. On the left-hand side,  
278 the heating rate is higher (so during the first 20 h), thermal expansion on the left-hand side is  
279 higher than the right-hand side. This thermal expansion in the left-hand side was then "restrained"  
280 by the right-hand side of the wall. At the same time, the vertical expansion of the wall mobilizes  
281 the shaft friction along its interface in contact with the soil mass. That mobilized shaft friction  
282 tends to prevent the wall vertical expansion, increasing then the vertical stress inside the wall. On  
283 the other hand, the sensors located at larger depths (1.67 m) are subjected to higher increase of  
284 vertical stress. That explains the compression of the wall during the first hours on the left-hand  
285 side at large depths and tensile stress on the right-hand side.

286

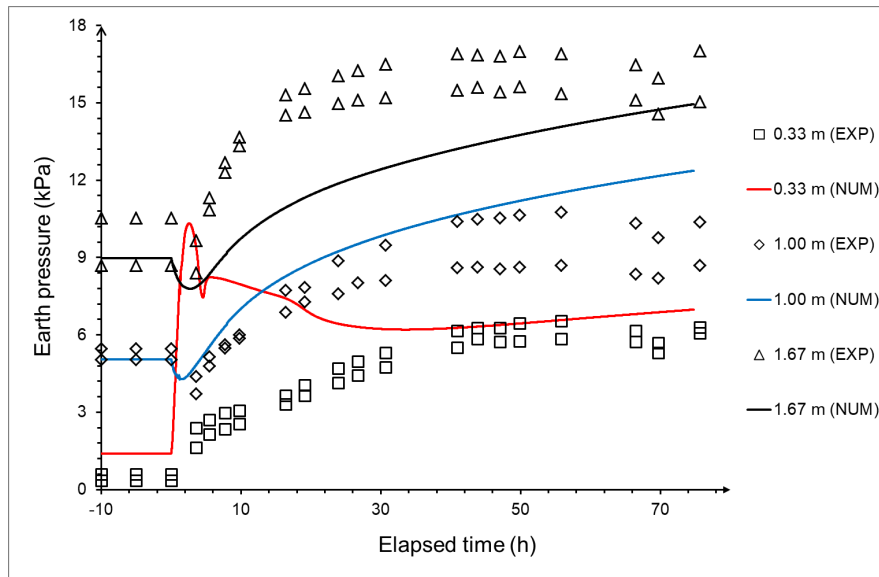
287 Figure 7 shows the normal stress on soil-wall interface versus elapsed time at various locations.  
288 The initial value of the lateral earth pressure is approximately 1 kPa at 0.33 m depth, 5 kPa at 1.00  
289 m depth and 9 kPa at 1.67 m depth. On the left-hand side (Figure 7a), at 0.33-m depth, there is  
290 only one transducer. The measurement shows a quick increase of the earth pressure following the  
291 heating phase, and the value at stabilization is approximately 4 kPa. At 1.00-m depth, there are  
292 two sensors both showing a quick increase of the earth pressure and the final values are  
293 approximately 11 kPa. The discrepancies between the two sensors are around 1 kPa. The sensors

294 at 1.67-m depth show similar trend with the final values close to 16 kPa. As a conclusion, for the  
 295 left-hand side, the variation of earth pressure is more significant at greater depth during heating.



296  
 297

(a)



298  
 299

(b)

300 Fig.7 Stress versus elapsed time at various depths on the left-hand side (a) and on the right-  
 301 hand side (b).

302

303 The general trend observed on the right-hand side is different at the start of heating (Figure 7b).  
304 At 0.33-m depth, the two earth pressure sensors show quick increase with the heating and the final  
305 average value equals 6 kPa, with a discrepancy of less than 0.5 kPa. At 1.00-m depth, both sensors  
306 show first a decrease of the earth pressure during the first hours of heating. These values increase  
307 and reach around 9 kPa at the end (with a discrepancy of 1 kPa). For the sensors at 1.67-m depth,  
308 the earth pressure increases with the heating and reaches 15 -17 kPa at the end. It could be seen  
309 there are still increase of pressure on both side at end of the test, this may due to a minor problem  
310 with the measurement.

311

312 The numerical results corresponding to the sensors at 1.00-m and 1.67-m depths show good  
313 agreement with the experimental ones for both sides. Even the decrease of the earth pressure at  
314 1.00-m depth on the right-hand side was well predicted. However, the numerical results  
315 corresponding to lower depth (0.33 m) are significantly different from the experiment values. On  
316 the left-hand side, the numerical simulation shows a decrease of earth pressure during the first  
317 hour, which was not observed in the experiment. On the right-hand side, the earth pressure spikes  
318 during the first hour, which was not observed in the experiment. These problems would be  
319 explained by the mechanical behavior of the sand in higher deflections [36, 39] under low stress  
320 level that could not be well predicted by FEA. This could also explain why was there reasonable  
321 accord before heating.

322

323 In order to better understand the results on the change of earth pressure (shown in Figure 7), the  
 324 deformed mesh (5 h after the starting of the heating) is shown in Figure 8. Heating induces thermal  
 325 expansion of the wall. That tends to increase the earth pressure at the soil/wall interface. However,  
 326 as the pipes were located closer to the left-hand side, the temperature distribution is non-uniform.  
 327 With the temperature on the left-hand side increasing more quickly than that on the right-hand  
 328 side. This induces a bending of the wall that can be seen clearly in the Figure 9. This bending  
 329 contributes also to the modification of the earth pressure. Besides the increase of earth pressure  
 330 related to the wall expansion, the wall bending decreases the earth pressure (mostly on the top) on  
 331 the left-hand side and increases that on the right-hand side. That explains why the increase of earth  
 332 pressure at 0.33-m depth on the right-hand side is higher than those at higher depth and the order  
 333 is opposite on the left-hand side. In addition, the bending of the wall also explains the decrease of  
 334 earth pressure observed at 1.00-m depth on the right-hand side during the first few hours.

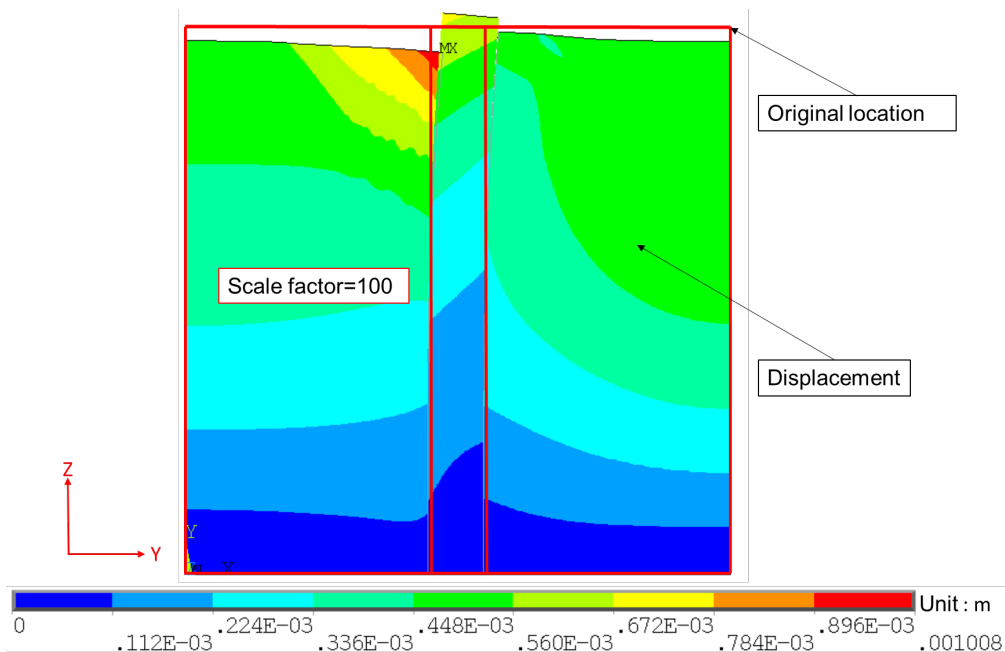


Fig.8 Deformed mesh at 5 hours (the color represents the sum of Y and Z displacement



337 vectors).

338

## 339 **5. Discussion**

340 In the present work, a 1-g physical model was used to study the thermo-mechanical behavior of  
341 an energy wall panel. Strainmeters were used to capture the axial strain inside the wall and earth  
342 pressure transducers were used to capture the normal stress at the soil/wall interface. This  
343 approach has been used in various studies to investigate the mechanical behavior of geostructures  
344 [40-42]. The results obtained in the present work show that this method could be also used to  
345 investigate the thermo-mechanical behavior of energy geostructures.

346

347 As far as the numerical model was concerned, the present study used a plane strain 2D FE model  
348 that approximates the conditions of the experiment. Even if this model could not capture the 3D  
349 heterogeneity of the temperature distribution, related to the difference between the inlet and outlet  
350 temperatures, a generally good agreement between the numerical and the experimental results can  
351 be observed. This confirms also that the boundary conditions and the constitutive laws used in  
352 this model are suitable for this case. Note that, for studying the thermal behavior of energy  
353 geostructures, usually only heat conduction is considered for heat transfer in the soil and in the  
354 reinforce concrete [29, 30, 43] unless ground water flow is present [7, 44, 45]. Heat convection in  
355 heat exchange pipe was discussed in the literature [32] and the heat transfer mechanism between  
356 the fluid and the pipe is more complex to be simulated [46, 47]. The hypothesis of elastic  
357 deformation is usually used for gravel soils in numerical simulation because it is in agreement

358 with experimental observations [27, 29, 48, 49]. In some cases where clayey soils were considered,  
359 more complex constitutive laws maybe required [50-53]. As mentioned above, to simplify the  
360 model, the heat exchange pipe is often represented by a line with controlled temperature [26]; The  
361 thermo-mechanical behavior of the soil was assumed to be elastic and the effect of temperature  
362 on the soil mechanical properties was ignored.

363

364 Both numerical and experimental results obtained in the present work evidence that heating the  
365 diaphragm wall induces thermal expansion and this increases the lateral earth pressure applied on  
366 the wall surface. The lateral earth pressure could be three times larger than the initial stress value  
367 under low stress level. This variation seems to have a significant contribution to the vertical stress  
368 within the wall. Previous studies on energy pile indicate that radial contact pressures typically  
369 increase less than 5 kPa along 20 m depth of the pile under an increase of 25°C of the pile  
370 temperature [33, 34]. In real scale structures, the height to width ratio could be much higher than  
371 the ratio in this physical study (equal to 10). As a result, the increase of lateral earth pressures  
372 might be negligible with respect to the variations of vertical stresses. However, for an energy pile,  
373 the increase of this pressure is almost homogenous because the layout of the pipes is usually  
374 symmetric. For diaphragm walls, the behavior is more complex and strongly depends on the  
375 distribution of the heat exchange pipes inside the wall. The eccentric position of the heat  
376 exchanger loop caused a temperature gradient across the wall thickness, which leads to wall  
377 bending. This phenomenon exists also in the wall that is not fully embedded [31], since the  
378 temperature condition on the soil side is different from the temperature condition on the

379 excavation side. This represents an additional contribution to thermally-induced vertical strains  
380 that are not uniform on the two sides of the wall.

381

## 382 **6. Conclusions**

383 The thermo-mechanical behavior of energy wall panel during heating was investigated using both  
384 physical and numerical models. The following conclusions can be drawn:

385

- 386 - Heating induces thermal expansion of the wall. The vertical thermal expansion mobilizes the  
387 shaft friction between the soil and the wall and then modifies the axial stress state inside the  
388 wall. Horizontal expansion increases the earth pressure at the soil/wall interface, and thus  
389 increases the mobilized shaft friction along the wall and the vertical stress inside the wall.
- 390 - As the pipe layout was not symmetric, thermal expansion bends the wall resulting in different  
391 stress/strain response between the two sides.
- 392 - A short-term heating of the wall shows a significant temperature gradient across the wall  
393 thickness. As a result, significant stress/strain variation is generated within the wall during  
394 the first few hours.
- 395 - The numerical model using an elastic law for the thermo-mechanical behavior of soil is  
396 appropriate to predict the behavior of the wall under thermal loading. There is however some  
397 discrepancy between experiment and numerical results that requires a deeper investigation,  
398 i.e. soil behavior at low stress level, 3D effect in the numerical model, etc.

399 - In spite of the temperature difference between the outlet and inlet fluid temperature, that  
400 induced a non-uniform temperature distribution inside the wall, a 2D numerical model seems  
401 appropriate to predict the main features of the panel's thermo-mechanical behavior observed  
402 by physical model.

403

#### 404 **Acknowledgement**

405 This research was supported by the National Natural Science Foundation of China (grant  
406 number 41272314); and Science and Technology Project of Suzhou (grant number  
407 SYG201451); and the European Commission via the Marie Curie IRSES project GREAT  
408 'Geotechnical and geological Responses to climate change: Exchanging Approaches and  
409 Technologies on a world-wide scale' (grant number FP7-PEOPLE-2013-IRSES-612665).  
410 Thanks are also due to Yinkang Zhou from Nanjing University for valuable discussion.

411

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