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#### 8 Abstract

9 Underground geotechnical structures, such as deep and shallow foundations, diaphragm walls, tunnel linings 10 and anchors are being increasingly employed as energy geostructures to exchange heat with the ground by 11 installing absorber pipes into the structural elements. This paper focuses on the application of this technology to reinforced concrete diaphragm walls used for construction of underground car parks, basements and metro 12 stations, with the purpose of heating and cooling the adjacent buildings. Preliminary numerical modelling 13 allowed optimising the geothermal plant design of the diaphragm wall. Then its energy efficiency is 14 investigated through finite element thermo-hydro coupled analyses together with the effects of the thermal 15 activation on the surrounding soil. Finally, finite difference thermo-mechanical analyses are used to study the 16 mechanical effects induced by the thermal activation. 17

Keywords: energy walls, energy geostructures, thermo-hydraulic numerical analyses, thermo-mechanical
 numerical analyses, shallow geothermal energy

20

#### 21 1. Introduction

Underground geotechnical structures, such as deep and shallow foundations, diaphragm walls, tunnel linings 22 and anchors are being increasingly employed as energy geostructures, in Europe and all around the world 23 [1,2]. Research studies on this technology are increasingly being carried out, including investigations on 24 their energy efficiency and geotechnical behaviour [3-7]. Besides being constructed for their primary 25 structural role, they are equipped to be able to exchange heat with the ground and supply thermal energy for 26 heating and cooling of buildings and de-icing of infrastructures. This technology can play a fundamental role 27 in the current challenge of facing the increasing need for clean and renewable sources of energy. The thermal 28 29 activation is achieved by installing absorber pipes in the geostructures, in which a circulating fluid extracts or injects heat from or into the ground. The polyethylene Pe-Xa pipes are usually attached to the reinforcing 30 steel cage, before concrete cast. The pipes inlet/outlet of each panel are connected to the main circuit, which 31 links them to the heat pumps. 32

These systems belong to the category of low enthalpy geothermal plants and are associated with heat pumps.
 A number of real applications of this technology are already operational especially in Austria, Germany,
 United Kingdom and Switzerland [8–15].

This paper focuses mainly on the application of this technology to the diaphragm walls of underground car parks, basements and metro stations, with the purpose of using them for heating and cooling the adjacent buildings. Efforts have already been devoted to study similar applications [4,16–19] and a number of real operational systems exist [20–22].

The main goals of this study were to optimise the heat exchanger pipe circuit in the walls, quantify the
extractable and injectable heat, and study the consequences in terms of structural behaviour and effects on
the surrounding ground.

A reference diaphragm wall, with the geometry shown in Figure 1 was considered in all the simulations
presented in this paper, i.e. a wall panel 2.5 m wide, 0.8 m thick and 15.5 m deep. The absorber pipes are
installed only on the ground side. Another solution would have been to have a double circuit, one on each

side, in order to foster the heat exchange with the air inside the excavation. The efficiency of this solutionneeds to be checked.

48 Preliminary numerical analyses were conducted to assess the optimal geothermal plant design for the 49 diaphragm wall. Then, three main aspects were investigated with reference to the optimal setting: the energy 50 performance, the temperature variation in the surrounding soil and the mechanical effects induced on the 51 wall by its thermal activation.

#### 52 **2.** Energy performance and thermal aspects

53 With the aim to assess the energy efficiency of thermo-active walls analysing the thermal exchange between 54 the fluid circulating through the pipes, the concrete structure and the surrounding saturated soil, thermo-55 hydro simulations were performed through the finite element software FEFLOW© [23]. The procedure 56 adopted is consistent to that described in [24] for energy tunnels.

57 The thermo-hydro problem is governed by the mass conservation equation, the energy conservation equation58 and the Darcy's velocity law.

The absorber pipes were reproduced through the 1D discrete features elements provided in the software. The use of these elements to simulate pipes in geothermal systems has been validated and showed good agreement when compared to analytical solutions [23]. In this study, the pipes are considered to have a diameter of 25 mm and thickness of 2.3 mm. The material properties used in the simulations are listed in Table 1. Parameters related to the ground are representative of the Torino (Italy) subsoil, according to previous studies where specific pumping tests were executed [25].

65

#### 66 2.1. Study on the pipe configuration and fluid velocity

67 The geometry of the pipe circuit is a compromise between the construction feasibility and the optimised heat68 exchange.

69 Simplified models were built in order to identify the most efficient configuration in terms of heat exchange, 70 depending on the position of the pipes and the fluid velocity. The initial temperature was set equal to 14 °C 71 for the whole domain, while the ground water level was set to 5 m below the ground surface. For the sake of 72 simplicity, no ground water flow was considered in these preliminary analyses. The bottom and far field boundaries (left side in Figure 2a) were checked to be far enough not to influence the results. External air 73 74 temperature was imposed on the top boundary, considering the seasonal fluctuation in the city of Torino (based on data from [26]), representative of a temperate humid European climate, according to Figure 2b. 75 76 The choice of the wall thermal boundary condition (interior of the tunnel or car park or basement) is one of 77 the most peculiar aspects of energy walls or tunnels modelling, as it represents a major difference with respect to more conventional borehole heat exchangers or energy piles, which are surrounded by soil 78 79 [3,6,27]. However, for these preliminary analyses which have the purpose to find the most efficient solution 80 and not to provide reliable data of exchanged heat, adiabatic condition was imposed on the right side of the 81 model. For the thermal-hydraulic analysis, the model was firstly run for one year without activation of the 82 geothermal plant to initialise the soil temperature according to the external air variation. The plant was then activated by injecting water into the pipes at a constant inlet temperature of 4°C for one month (Figure 2b), 83 84 reproducing the heat extraction condition (winter mode). Three pipe configurations were considered, as illustrated in Figure 3. It has to be noticed that the pipes length is different for the three configurations, i.e. it 85 is 55.5 m for case (a), 68.0 m for case (b) and 50.0 m for case (c). For the three configurations, the analyses 86 87 were repeated for different values of fluid velocity, between 0.1 and 1.0 m/s. The exchanged heat, expressed 88 in Watt was computed as:

$$Q = mc_w |T_{wo} - T_{wi}| \tag{1}$$

89 where *m* is the mass flow rate inside the pipes expressed in kg/s,  $T_{wo}$  the fluid outlet temperature and  $T_{wi}$  the 90 imposed fluid inlet temperature.

- 91 The results obtained for the three pipe configurations and imposing a fluid velocity of 0.6 m/s are reported in
- 92 Table 2. The exchanged heat per linear meter,  $Q_l$  is intended per meter of pipe, while that per square meter,
- 93  $Q_s$ , is intended per wall surface area. Configuration (c) appears to be the most favourable. This result is in 94 agreement with the outcome of a similar study carried out by [19], although other studies highlighted
- 95 concerns about the practical applicability of such horizontal configuration [20]. Because of the amount of
- reinforcement usually used in diaphragm walls, placing pipes horizontally might be more difficult and it may
- affect the way in which the concrete spreads in the trench to more extent than the vertical placement.
- Figure 4 shows the influence of the fluid velocity on the exchanged heat for the pipes configuration (c). All considered velocities allow for a turbulent flow to occur into the pipes. Differently from the case of energy tunnels [3], the fluid velocity does not affect the exchanged heat in a significant manner. However, this was also confirmed by other similar studies on energy piles and walls [4,19,28]. Considering these results and the

mentioned difference in pipes length, configuration (c) was chosen as the optimised one in the following,

101 102 103

# 104105 2.2. Quantification of heat exchange potential

assuming a fluid velocity of 0.2 m/s.

A more advanced 3D numerical model was built to properly quantify the exchangeable heat. The model 106 reproduces with more details the geometry of the diaphragm wall by including a 1.0 m thick concrete slab 107 which constitutes the base of the excavation, at 9.5 m below the ground surface (Figure 5a). The surrounding 108 ground is also included with the dimensions shown in the same figure. The bottom, left and right boundaries 109 were checked to be far enough not to influence the results. The same external air temperature seasonal 110 variation was adopted and imposed to the top boundary. The assumption on how to model the internal air 111 was previously studied by [27] and the comparison between different boundary conditions showed that 112 modelling the air is equivalent to consider the wall as adiabatic and was adopted in the following. Air was 113 thus modelled through finite elements, having air thermal properties. This assumption is the most 114 conservative in terms of energy efficiency, because the heat exchange between the wall and the air is 115 neglected. Two groundwater flow conditions were considered: (i) no flow and (b) ground water flow velocity 116 of 1.5 m/d. Based on the previous analysis, the inlet fluid velocity was assumed equal to 0.2 m/s. 117

118 The time frame in the analysis is 4 years. The first year reproduces the situation before the activation of the geothermal plant, where only the external air temperature is present. This is followed by three years of 119 heating-cooling mode. A double mode usage of the geothermal plant was considered, including three months 120 heating and three months cooling, according to the input presented in Figure 5b. It is to be mentioned that 121 this condition does not fully reproduce the proper behaviour of a real heat pump system where the 122 temperature of the fluid would be the result of the use of the heat pump and, generally, will not remain 123 constant over a season. Although real systems operate within varying and complex energy demand (and 124 hence inlet temperature) patterns, a constant temperature has been used in the following to provide (a) a 125 simpler and controlled conditions comparison of the parameters under consideration and (b) a more generally 126 applicable approach within the wide range of thermal demand scenarios relevant to different building 127 128 typologies.

The obtained results are illustrated in Figure 6a and 6b, in terms of inlet/outlet temperature and exchanged heat per meter of wall depth, respectively. It can be concluded that the heat exchange is highly affected by the presence of the ground water flow, as confirmed by similar studies [29]. The peak and end of cycle values of exchanged heat in winter and summer conditions for the two-considered ground water flow velocities are presented in Table 3 and Table 4. It has to be noticed that these results are valid for the considered geometry and conditions, i.e. for the upstream side of the structure.

To quantify the effective benefit in using this technology, the obtained results in terms of heat exchange were compared with the average energy demand of a typical apartment building. Data on energy consumption for heating were extracted from the database delivered by the European project Tabula [30], which provides an overall figure of energy demand in Europe for several typical buildings. The apartment block building

139 typology for a middle climatic zone (Italy) was selected from the database. As the energy demand seems to be highly influenced by the construction period due to the continuum innovation in the refurbishment 140 process, two construction periods were considered, i.e. early 1900 and after 2006. Two different heat supply 141 systems correspond to the two selected periods, both based on a gas central heating system. A non-142 condensing boiler (atmospheric burner), central distribution and gas-fired instantaneous water heater was 143 considered for the 1900 constructions while a low temperature standard boiler and gas-fired instantaneous 144 water heater with condensing plus thermal solar plant was considered for most recent constructions. 145 146 Assuming to turn on the geothermal system for 1800 hours per year for heating during winter, the number of energy wall panels needed for heating was computed. Table 5 illustrates the results of this analysis for both 147 the considered groundwater flow conditions. The number of panels needed for apartment buildings are in 148 line with the geometry that an underground car park for the residents' use would likely have. This is 149 particularly true with the today's figures in terms of energy needs, showing that application of energy 150 geostructures is promising if considered from the design stage of new construction. 151

#### 152 **2.3.** Thermal effects on the surrounding soil

In order to evaluate the influence on the ground temperature, Figure 7 shows its evolution 5 m far from the wall contour, at different depths in the case of no flow and of groundwater flow of 1.5 m/d. Up to about 5.5 m depth (point A in Figure 5) the ground temperature is affected by the external air temperature fluctuation (see first year results). The activation of the geothermal system induces a variation of temperature in both points A and B of +/- 1.5 °C with respect to the temperature variation experienced during the first year of simulation.

#### 159 **3.** Thermo-mechanical aspects

When the diaphragm wall is used as ground heat exchanger, it is subjected to seasonally cyclic temperature 160 variations. This could have different consequences: on the one hand, the wall could undergo thermal 161 deformation according to its constitutive behaviour, on the other hand, its thermal deformation could be 162 partially prevented by the surrounding soil and possible over structure thus inducing additional stresses. As 163 164 the primary structural role of the retaining structure must always be ensured, 2D plane strain thermomechanical analyses were conducted to investigate the thermal-induced mechanical effects on the diaphragm 165 wall caused by its thermal activation. The Finite Difference Method (FDM) software FLAC [31] was used 166 167 for this purpose.

#### 168 **3.1. Mathematical formulation**

The thermal option of FLAC incorporates both conduction and advection models, but only conduction was 169 170 considered in the following analyses. The heat transfer and the consequent temperature changes are coupled to the mechanical calculations at any time during a transient simulation. The coupling occurs in one direction 171 only, i.e., the temperature may result in stress changes, but mechanical changes in the body resulting from 172 force application do not result in temperature change. This restriction is not believed to be of great 173 significance here, since the energy changes for quasi-static mechanical problems are usually negligible. Both 174 soil and concrete are assumed to behave thermo-elastically and consequently their thermal deformation  $\varepsilon_{ij}^{T}$  is 175 176 computed as:

$$\frac{\partial \varepsilon_{ij}^{T}}{\partial t} = \beta \frac{\partial T}{\partial t} \delta_{ij}$$
<sup>(2)</sup>

where t is the time, T is the temperature,  $\beta$  is the coefficient of linear thermal expansion [1/°C] and  $\delta_{ij}$  is the Kronecker delta. From this, constitutive equations are reformulated to solve thermal stress problems [31]. The differential equation of motion and the rate of strain-velocity relations used in the FDM are based upon mechanical considerations and are unchanged for thermo-mechanics.

#### 181 **3.2. Structural behaviour**

182 Numerical analyses were performed with reference to the geometry of the reference diaphragm wall and 183 positioning of the geothermal pipes adopted for thermo-hydraulic analyses. The mesh characteristics and

dimensions (14880 quadrilateral elements) are shown in Figure 8 together with the boundary conditions adopted. Plane strain conditions are assumed to hold true. Particular care was adopted to include the correct size of the pipes in the mesh as shown in the same Figure 8. Thermal parameters adopted are the ones given in Table 1, while mechanical parameters were chosen based on previous studies [32] and are listed in Table 6. Elastic perfectly plastic behaviour was assumed for the soil while a linear elastic behaviour for concrete.

189 The numerical analysis is performed in different stages. A first group of stages is used to assess the stress state in the ground resulting from the construction of the diaphragm wall and the base slab, before the 190 geothermal system is activated. Only mechanical loading is applied during these stages. The construction of 191 the diaphragm wall is simulated by applying appropriate mechanical parameters to the finite elements in the 192 corresponding wall area. The excavation is then performed in three subsequent stages (two first layers of 3.2 193 194 m and a third layer of 3.1 m), obtaining a final excavation depth of 9.5 m. The base slab is afterwards installed by applying the mechanical properties of concrete to the corresponding finite elements. For the sake 195 of simplicity, the seepage problem arising by excavating below the ground water table is not considered in 196 the computation (TM simulations). 197

A second group of stages simulates the operation of the geothermal system. For these stages, the thermo-198 199 mechanical coupling is activated. Thermal boundary conditions in the model are consistent to those adopted for the thermo-hydraulic analysis previously described. The internal boundary on the car park side is 200 assumed with a fixed temperature of 14°C, considered as the mean value year-round. The model is firstly 201 202 subjected to the variation of the external air temperature only, for the period of 3 years (starting from 1<sup>st</sup> January). The external air temperature is the same as that adopted for thermo-hydraulic analyses and shown 203 in Figure 5b. Then, the operation of the geothermal system is simulated for a period of 1000 additional days 204 (i.e. 2 years and 270 days). This is done by applying an input temperature to the nodes of the elements which 205 reproduce the pipes contour. The input temperature is varied along the year, following the heating and 206 cooling cycles, by applying the corresponding values determined from the thermo-hydraulic analyses, 207 averaged over the pipes length. 208

209 Figure 9, shows the temperature distribution in the wall and ground with colour scale labels, for two moments, representative of the summer (August) and winter (February). This is shown to be in fair 210 agreement with the data from thermo-hydraulic analyses of Figure 7. However, some time shift is present, 211 212 due to the different assumption for thermal flow and for the boundary condition adopted at the wall internal 213 side between the thermo-hydraulic and the thermo-mechanical analyses. Also, advection is not considered in the TM analyses. While it plays a major role when assessing the temperature distribution in the ground (it 214 was included in fact in the TH analyses), it does not influence much the temperature distribution within the 215 wall itself. The comparison between the computed temperatures (Figs. 7 and 9) is considered in sufficient 216 217 agreement to justify neglecting advection.

To evaluate the thermal induced stress strain behaviour of the wall, Figure 10 shows the horizontal displacement at the top of the diaphragm wall and the temperature variations, computed for some selected measuring points located at different depths from the top of the diaphragm wall (at 3.5 m, 9.5 m and 16 m). Selected measuring points located at the same depth (9.5 m) but at different distances from the diaphragm wall (on the pipes axis, 1.2 m and 3.2 m on the ground side) are shown instead in Figure 11. Both figures show data pertaining to the stages when the geothermal system is in operation; starting values in the plots correspond to the results of the construction stages.

It is shown that during the first three years, the temperature change is strictly dependent from the external air temperature for point A, while points B, C, D and E are ranging around a constant value due to their depth. Moreover, some deviation with time occurs to the horizontal displacement at the top of the diaphragm wall. Two full year cycles are needed before the seasonal fluctuation reaches equilibrium (this was verified by running a separate thermo-mechanical analysis where only the external air temperature effect is considered up to four years cycle).

When the geothermal system is activated, the temperature change in the points is strictly dependent from the input temperature in the pipes. This influence is reduced for point C, in the ground below the diaphragm wall. Again, an initial deviation with time of the stresses and displacements computed is experienced and

becomes negligible only after the first two years of activation. Temperature changes of points B, D and E are
shown to slowly decrease while moving further from the pipes, also, the temperature peaks are shifted in
time due to the thermal inertia of the soil.

Thermal cycles in the pipes cause deformation of the original wall deflection. Figures 12a and 12c show the 237 238 horizontal displacements computed along the diaphragm wall vertical axis. Maximum displacement variation with respect to undisturbed state is shown for that pertaining to summer operation mode (August, Fig. 12a) 239 240 and to winter operation mode (February, Fig. 12c). Also shown in the same figures are the displacements computed during mechanical loading. As the top wall deformation is not restricted, the deflection due to 241 thermal cycles is quite evident, ranging between 16 to 22 mm (the maximum values are obtained during 242 summer). This corresponds to a 16% displacement increase during summer and a 4% decrease during winter 243 induced by the thermal activation of the geothermal system. The variation in terms of bending moment 244 during heating and cooling cycles, is shown in Figures 12b and 12d. At the base of the wall, the presence of 245 the base slab and the ground creates constraints to wall movements. Thermal induced horizontal 246 displacements are negligible, while the corresponding stress change rises up producing a maximum bending 247 moment of 460 kNm/m during winter (i.e. an increase of 17%). Bending moment is minimum during 248 Summer, when the displacement is maximum, and reaches highest values in winter. The stress variations 249 computed in the analyses are largely below the strength limits of the structure. 250

Similar analyses conducted by [6] have shown minor displacements at the head as an effect of thermal 251 activation (less than 10 mm). However, in the mentioned study, despite minor variation in parameters and 252 geometry, a major difference lied in the fact that the diaphragm wall was subjected to different constraints. A 253 top slab was present in [6] study, whereas here the diaphragm wall is considered unrestrained at the top, to 254 investigate a different restraint configuration. An additional numerical analysis was carried out by 255 constraining the top of the diaphragm wall by a roller (i.e. similar conditions to the [6] study). The results 256 confirmed lower displacements and bending moments along the diaphragm wall with respect to the non-257 258 constrained configuration. The latest, presented in this paper, can therefore be considered a conservative condition. Moreover, this is a clear (and rather obvious) indication that the mechanical effects of thermal 259 loading on diaphragm wall are strictly function of the structural conditions. This implies that the proper 260 261 construction sequence and structural behaviour need to be properly simulated in the numerical analysis to allow for reliable results to be obtained. 262

263

## 264 **4.** Conclusions

265 Based on the results of the computations described, one can draw the following conclusions:

- The horizontal configuration of pipes geometry allows maximising the heat exchange.
- The energy wall system for the conditions considered in this paper would allow to exchange between
   20 to 25 W per square meter of wall, in Winter and in Summer respectively, when the ground water
   is static, that rises up to 40 to 50 W/m<sup>2</sup> when a favourable underground water flow exist.
- These figures would allow to cover energy needs of a typical apartment building, imaging to thermally activate an underground car park serving the building.
- The influence on the surrounding ground in terms of temperature variation of the groundwater flow is within 7°C at 5 m distance from the wall boundary with full recovery after the year-round cycle starting from the second year of operation.
- Bending moment and horizontal displacement at the top of the diaphragm wall increase up to 16% due to thermal activation. However, stress variations computed are largely compatible with strength limits.

278 The above findings are in line with research results and case study data previously published and underline 279 the interest to improve the understanding of the geothermal process to enhance the potential use of 280 underground infrastructures as effective and innovative heat exchangers for the future.

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Property	Heat carrier fluid	Ground	Concrete
Horizontal hydraulic conductivity, k <sub>x</sub> =k <sub>z</sub> [m/s]	-	4.15 10-3	10-16
Vertical hydraulic conductivity, ky [m/s]	-	$2.075 \ 10^{-4}$	$10^{-16}$
Specific storage coefficient, S [m <sup>-1</sup> ]	-	$10^{-4}$	10 <sup>-4</sup>
Porosity, n [-]	-	$0.25 \div 0.3$	0.0
Heat capacity, $\rho c [MJ/m^3/K]$	4.2	2.55	2.19
Thermal conductivity, $\lambda$ [W/m/K]	0.65	$2.26 \div 2.8$	2.3
Longitudinal dispersivity, $\alpha_L$ [m]	-	3.1	-
Transverse dispersivity, $\alpha_T$ [m]	-	0.3	-

Table 1 – Material properties (Barla et al., 2013).

Table 2 – Extracted heat in the different configurations considered (fluid velocity = 0.6 m/s).

	$\varrho$	$Q_l$	$Q_s$
	[W]	[W/m]	$[W/m^2]$
(a) VP	290.11	5.22	7.49
(b) HP - i=0.5m	324.09	4.76	8.36
(c) HP - i=1.0m	313.71	6.26	8.10

Table 3 – Extracted and injected heat with no ground water flow.

	Peak	End of cycle	Peak	End of cycle
	W/m	W/m	W/m <sup>2</sup>	W/m <sup>2</sup>
Winter	51.0	17.2	20.4	6.9
Summer	63.0	24.0	25.2	9.6

 $Table \ 4-Extracted \ and \ injected \ heat \ with \ a \ ground \ water \ flow \ velocity \ of \ 1.5 \ m/day.$ 

	Peak	Steady state	Peak	Steady state
	W/m	W/m	W/m <sup>2</sup>	W/m <sup>2</sup>
Winter	98.8	70.4	39.5	28.1
Summer	123.5	90.4	49.4	36.2

Table 5 – Examples of possible applications for a common building typology: apartment block (data on energy demand from Corra	ado
et al., 2012).	

Construction	Total Energy	Exchar per wa [k	nged heat all panel xW]	Operation duration	Exchar per wa [k	nged heat all panel Wh]	Number pa	of needed
period	[MWh]	gwf=0 m/d	gwf=1.5 m/d	[h]	gwf=0 m/d	gwf=1.5 m/d	gwf=0 m/d	gwf=1.5 m/d
Today	113.5	0.27	1.1	1900.0	196.0	1062.0	233	58
1900	270.5	0.27	1.1	1800.0	480.0	1962.0	557	138

Table 6 – Geotechnical parameters adopted for the thermo-mechanical numerical analysis.

Property	Ground	Concret
Unit weight [kN/m <sup>3</sup> ]	19.5	25
Elastic modulus [MPa]	215	33300
Poisson's ratio [-]	0.3	0.2
Bulk modulus [MPa]	179	18500
Shear modulus [MPa]	83	13875
Cohesion [kPa]	15	-
Friction angle [°]	38	-
Thermal conductivity, $\lambda [W/m/K]$	2.8	2.3
Linear thermal expansion, $\beta$ [1/°C]	10 <sup>-5</sup>	$1.2 \cdot 10^{-3}$
Specific heat [J/kg°C]	1053	876



Figure 1- Geometry of the reference energy wall panel.



Figure 2 – (a) Geometry and boundary conditions of the FE model and (b) external air and inlet temperature.



Figure 3 - Pipes configurations.



Figure 4 – Extracted heat as a function of the heat carrier fluid velocity in the pipes.



Figure 5 – (a) Geometry of the model and (b) imposed cyclic inlet temperature and external air temperature variation in Torino.



Figure 6 - (a) Inlet and outlet temperature in the pipes and (b) exchanged heat during three years' simulation, in the case of 0 and 1.5 m/day of ground water flow.



Figure 7 – Temperature variation in the ground 5 m far from the wall at different depths, in the case of 0 and 1.5 m/day of ground water velocity.



Figure 8 – Finite difference mesh adopted for thermo-mechanical analyses: model, size, boundary conditions and detail of the mesh in the pipe area.



Figure 9 – Temperature distribution in °C in the ground in August (a) and February (b) with the geothermal system activated.



Figure 10 – Displacement at the top of the diaphragm wall, input temperature variation in the pipes and external air temperature assumed during computation compared to that computed at specific measuring points (A, B, C).



Figure 11 – Displacement at the top of the diaphragm wall, input temperature variation in the pipes and external air temperature assumed during computation compared to that computed at specific measuring points (B, D, E).



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10

11

12

13

14

15

16

Base slal

(c)

Depth [m]



(d)

Figure 12 – Bending moment and horizontal displacement change with: mechanical loading, external air and the activation of the geothermal system in Summer (August, (a), (b)) and Winter (February, (c), (d)).

Mechanical loading

Ext. air: 1st year

Ext. air: 2nd year

Ext. air: 3rd year

Input: 4th year

Input: 5th year

Input: 6th year

#### Bending moment [kNm/m]

100

0

-100

200

300

400

- Thermal and mechanical aspects of energy walls are discussed.
- The horizontal configuration of pipes geometry allows maximising the heat exchange.
- Heat exchange between 20 to  $25 \text{ W/m}^2$  with static ground water.
- Heat exchange between 40 to 50  $W/m^2$  with favourable groundwater flow.
- Bending moment increase up to 16% due to thermal activation.