



HAL
open science

A simple load transfer method for energy pile groups

Huaibo Song, Huafu Pei, Jean-Michel Pereira, Anh Minh A.M. Tang, Chao Zhou

► **To cite this version:**

Huaibo Song, Huafu Pei, Jean-Michel Pereira, Anh Minh A.M. Tang, Chao Zhou. A simple load transfer method for energy pile groups. *Computers and Geotechnics*, 2023, 159, pp.105483. 10.1016/j.compgeo.2023.105483 . hal-04375003

HAL Id: hal-04375003

<https://enpc.hal.science/hal-04375003>

Submitted on 14 Jan 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A simple load transfer method for energy pile groups

Huaibo Song¹, Huafu Pei^{2*}, Jean-Michel Pereira³, Anh Minh Tang⁴, Chao Zhou⁵

¹ Ph.D. student, MSc, School of Civil Engineering, State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China; Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France, E-mail: songhuaibo@mail.dlut.edu.cn; huaibo.song@enpc.fr, <https://orcid.org/0000-0002-4592-9521>

^{2*} Professor, Ph.D., School of Civil Engineering, State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China (corresponding author).
E-mail: huafupei@dlut.edu.cn, <https://orcid.org/0000-0003-3862-0865>

³ Professor, Ph.D., Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France,
E-mail: jean-michel.pereira@enpc.fr, <https://orcid.org/0000-0002-0290-5191>

⁴ Research Director, Ph.D., Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France, E-mail: anh-minh.tang@enpc.fr, <https://orcid.org/0000-0002-7149-8497>

⁵ Associate Professor, Ph.D., Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, HKSAR, China, E-mail: zhou@polyu.edu.hk

Abstract

Various analysis methods have been developed to simulate the performance of energy pile groups subjected to thermal and mechanical loads. Although they considered the interactions between piles in the group, the ‘sheltering-reinforcing’ effect was usually ignored during the analysis, or the methods were not experimentally validated. Therefore, to address this gap, we propose an experimentally validated load transfer model that considers the ‘sheltering-reinforcing’ effect for the thermomechanical analysis of energy pile groups. The proposed method modeled two well-documented full-scale field tests and two finite-element simulation cases. The comparison results showed that the proposed method could capture several essential aspects of the energy pile group, including thermally induced strain, stress, displacement, and group effects. Furthermore, a parametric analysis was performed to evaluate the effects of relevant parameters on the thermomechanical behavior of the energy pile group.

Keywords: load transfer method; energy pile group; thermomechanical behavior; geothermal energy.

1. Introduction

Energy piles are environment-friendly technologies that have attracted increasing attention

33 because of their effective solicitation of shallow geothermal energy (Rotta Loria and Coulibaly
34 2021). Unlike conventional pile foundations, the operation of an energy pile involves complex
35 coupling between thermal, mechanical, and other physical fields (Bourne-Webb and Bodas
36 Freitas 2020). It is also necessary to consider pile–pile and pile-slab interactions under thermal-
37 mechanical loading for energy pile groups (Moradshahi et al. 2020, Ravera et al. 2020a, 2020b,
38 Fang et al. 2022). Recently, understanding this complex mechanism, seeking simple approaches
39 to describe it, and then applying it to the engineering design of energy piles has become a hot
40 topic in energy pile research.

41 Numerous in situ field tests (Bourne-Webb et al. 2009, Murphy et al. 2015, Faizal et al.
42 2019, Sutman et al. 2019a, Fang et al. 2020, 2022, Wu et al. 2020, 2021), small-scale laboratory
43 model tests (Kalantidou et al. 2012, Yavari et al. 2016a, Yazdani et al. 2019b, Kong et al. 2020,
44 Song et al. 2020), and centrifuge model tests (Ng et al. 2015, 2016, 2021, Ng and Ma 2019)
45 have been conducted to investigate the thermomechanical behavior of energy pile and pile
46 groups. It is impractical to use experimental methods to comprehensively investigate the effects
47 of all the factors on the performance of energy piles considering the enormous time-consuming
48 and financial expense. Thus, the development of experimentally verified numerical methods to
49 supplement the experimental methods is necessary to thoroughly study the thermomechanical
50 mechanisms of energy piles. Various numerical approaches with different complexities have
51 been used in previous years, including finite element models (Yavari et al. 2014, Rammal et al.
52 2018, Garbellini and Laloui 2019a, Nguyen et al. 2019, Arzanfudi et al. 2020, Georgiadis et al.
53 2020, Sutman et al. 2020), finite difference models (Suryatriyastuti et al. 2012, 2014, Luo and
54 Hu 2019, Najma and Sharma 2021, Liu et al. 2022), and other theoretical models (Rotta Loria
55 and Laloui 2016, 2017a, Rotta Loria et al. 2018, 2020a, Garbellini and Laloui 2019a, Iodice et
56 al. 2020, 2023, Ravera et al. 2020a, 2020b, Cui et al. 2021, Saeidi Rashk Olia et al. 2022, Liu
57 et al. 2022, Song et al. 2022, Song and Pei 2022, Pei et al. 2022a). Among these, the load
58 transfer method is commonly used for energy pile design because it overcomes the drawbacks
59 of high time consumption, high computational cost, and high requirements of the complete

60 numerical simulation method. The load transfer method is very user-friendly and well-suited
61 for the engineering design of energy piles.

62 The load transfer method was initially proposed by Seed and Reese ([Seed and Reese 1957](#))
63 and then gradually applied to investigate the thermomechanical response of an isolated energy
64 pile. For example, Knellwolf et al. ([2011](#)) developed a load transfer method using the three-
65 polyline load transfer curve proposed by Frank and Zhao ([1982](#)). In situ isolated energy piles
66 were modeled, and their thermomechanical behavior was analyzed. The comparison results
67 between the simulations and the measured data showed good agreement. Sutman et al. ([2019b](#))
68 developed a model by incorporating the unloading-reloading response into the load transfer
69 curve and validated it through field test results. The above studies demonstrate the applicability
70 of the load transfer method for studying the thermomechanical response of an isolated energy
71 pile. As an essential part of the energy pile group, the successful application of the single pile
72 response model lays the foundation for developing a pile group response model.

73 Recently, several studies ([Ravera et al. 2020a](#), [Fei et al. 2022](#), [Liu et al. 2022](#)) extended the
74 load-transfer method to consider the thermomechanical interaction of energy piles in groups.
75 Ravera et al. ([2020a](#)) modified the load transfer curve of an isolated energy pile in a group using
76 a displacement factor that considered group effects. The field test results of an energy pile group
77 consisting of four energy piles were used to validate the proposed method. A comparison
78 between the simulated and measured results showed the suitability of the proposed method for
79 analyzing the thermomechanical performance of the energy pile group. Nevertheless, it should
80 be noted that the determination of the displacement factor is based on an empirical formula,
81 which is proposed based on the fitting of the finite-difference modeling results of the 5×5 pile
82 group ([Comodromos et al. 2016](#)). A significant difficulty in applying this empirical formula to
83 the analysis of the energy pile group is that the effect of the temperature on displacement factor
84 cannot be considered. Thus, additional experiments or numerical simulations are required for
85 specific analysis cases to comprehensively determine the appropriate displacement factors.
86 Besides, the load transfer method proposed by Ravera et al. ([2020a](#)) has some limitations in

87 clarifying the thermomechanical behavior of energy pile groups because it cannot take into
88 account the ‘sheltering-reinforcing’ effects of the energy pile group into consideration.

89 The ‘sheltering-reinforcing’ effects characterize the interaction between piles in groups and
90 are considered in previous studies of conventional pile groups (Mylonakis and Gazetas 1998,
91 Wang et al. 2016). The results indicated that the calculated pile head displacement was
92 overestimated without considering this effect, and the error increased significantly with
93 increasing group size. For the energy pile group, the ‘sheltering-reinforcing’ effects act
94 throughout thermomechanical loading, which can be observed in the field test results (Rotta
95 Loria and Laloui 2017b, 2018, Fang et al. 2020). Liu et al.(2022) proposed a load transfer
96 method to rapidly calculate the response of an energy pile group in which they considered the
97 reinforcing effect of neighboring piles in the group. The applicability of this method to pile
98 groups was verified by comparing it with finite element simulations that did not consider the
99 nonlinear pile-soil interaction (Rotta Loria and Laloui 2016). Nevertheless, the presence of the
100 slab and the pile-slab-soil interaction had not been considered in their study, which would limit
101 the scope of application of the method due to the importance of the slab in the energy pile group.
102 Besides, there is no adequate verification of whether the proposed model can accurately
103 calculate the critical aspects of the thermomechanical responses of the energy pile group,
104 including the pile axial strain, stress, and pile head displacement. Therefore, to address this gap,
105 it is necessary to develop an experimentally validated model.

106 This study aims to provide an experimentally validated simple load transfer model that
107 considers the ‘sheltering-reinforcing’ effects for thermomechanical analysis of energy pile
108 groups. Section 2 details the proposed model and the developed thermomechanical performance
109 analysis algorithm for energy pile groups based on the proposed model. Section 3 verifies the
110 results obtained by the proposed method using field tests and finite element simulations. A
111 comprehensive sensitivity analysis of the parameters involved in the proposed model is
112 presented in Section 4. Finally, conclusions are presented in Section 5.

113 2. Development of the load transfer model for the energy pile group

114 Some assumptions of the load transfer mechanism for energy piles are employed in this
115 study: (1) the load-displacement relationship (i.e., t-z model) and pile and soil properties are
116 assumed to be independent of temperature variations, based on the fact that previous studies
117 suggested that the effect of temperature within the range of 5 - 40 °C on soil and concrete
118 properties is insignificant (Yavari et al. 2016b, Yazdani et al. 2019a, Rotta Loria and Coulibaly
119 2021); (2) the strain and stress analysis of the energy pile in the group is achieved by
120 considering the pile-to-pile interaction in the pile group; (3) the interaction between the slab,
121 energy piles in the group, and soil can be considered through assuming an additional spring
122 connecting with the pile heads; (4) The influence of the axial deformation of the piles on the
123 thermomechanical behavior of the piles is mainly considered in the study to simplify the
124 calculation (Ravera et al. 2020a). The last assumption is based on the fact that a numerical study
125 of energy piles (Olgun et al. 2014) and full-scale field studies (Faizal et al. 2019) reported that
126 the normal contact stress of the piles did not change significantly owing to their radial thermal
127 expansion of the energy piles. Other studies on the load transfer analysis (Knellwolf et al. 2011;
128 Chen and McCartney 2016) have also confirmed that the influence of radial deformation on the
129 pile-soil axial interaction is negligible. Therefore, the present study did not consider the
130 influence of the radial deformation of the energy pile.

131 2.1 Load transfer function at the shaft of the isolated energy pile

132 According to a previous study (Lee and Xiao 2001), the nonlinear performance of the pile
133 load displacement is divided into (i) the nonlinear relationship between the pile shaft shear
134 stress and pile-soil relative displacement and (ii) the nonlinear stress-strain relationship of the
135 surrounding soil induced by the pile shaft shear stress. Caputo (1984) and Trochanis et al. (1991)
136 divided surrounding soil into disturbed and undisturbed zones. The disturbed zone is a thin
137 layer of soil on the soil/pile interface. The nonlinearity of the pile-soil interaction was
138 concentrated in this interface. The area outside the interface is the undisturbed zone. Because
139 this zone is subjected to a relatively low stress change, the stress-strain behavior of the soil is

140 mainly elastic. The nonlinear response of pile groups primarily depends on the nonlinear
 141 characteristics of single piles, and the pile-pile interaction is elastic. The total shaft
 142 displacement at a certain depth (i.e., u) can be divided into pile-soil relative displacement (i.e., p)
 143 and the elastic displacement of the surrounding soil (i.e., s). Recently, these concept has been
 144 introduced into the thermomechanical analysis of energy pile group (Fei et al. 2020, Liu et al.
 145 2022). As suggested by Lee and Xiao (2001), the thickness of the interface was assumed to be
 146 zero, which can provide a simplified mathematical processing method for simulating the pile-
 147 soil relative displacement and elastic displacement of the soil around the pile. Thus, the total
 148 pile shaft displacement can be expressed as follows:

$$149 \quad u = p + s \quad (1)$$

150 The elastic soil displacement induced by pile shaft stress can be calculated using the
 151 expression proposed by Randolph and Worth (1978):

$$152 \quad s = \frac{\tau r_0}{G} \ln \frac{r_m}{r_0} = \psi \tau \quad (2)$$

153 where G is the shear modulus of the soil, r_0 is the pile radius, r_m is the shear influence
 154 radius.

155 In this study, an exponential model was employed to calculate the pile-soil relative
 156 displacement of the pile-soil interface because it can better simulate the field test results without
 157 adopting complex fitting parameters (Kezdi. 1957). The exponential model is expressed as
 158 follows:

$$159 \quad \tau = \tau_u \left[1 - \exp \left(- \frac{G_{s,max}}{\tau_u} p \right) \right] \quad (3)$$

160 where τ is the pile shaft shear stress, τ_u is the ultimate shear stress, $G_{s,max}$ is the initial
 161 stiffness of the pile-soil interface, the unit of which is kPa/m.

162 It should be noted that the deformation mechanisms of energy piles and conventional piles
 163 differ. For the energy pile, when the pile body is heated up, it expands, the upper part of the pile
 164 side friction decreases, and it is in the unloading stage. In contrast, the shaft shear stress at the

165 lower end of the pile side increases and is in a loading state. When the pile body is cooled, it
 166 shrinks, and the situation is the opposite of that during heating. Therefore, Eq. (3) should be
 167 improved for the thermomechanical analysis of the energy pile. We developed a model by
 168 employing the improved Masing rule to simulate the loading-unloading-reloading path of the
 169 pile-soil interaction, and its expression can be written as Eq. (4). Further details can be found
 170 in (Pei et al. 2022b).

$$171 \quad \tau = \tau_0 + \eta(\tau_u - \eta\tau_0) \left[1 - \exp\left(-\eta \frac{G_{s,\max}}{\tau_u - \eta\tau_0} (p - p_0) \right) \right] \quad (4)$$

172 where η denotes the loading and unloading branching judgment factor, $\eta = -1$ and $\eta = 1$
 173 represent unloading and reloading conditions, respectively, p_0 denotes the relative
 174 displacement of the pile and soil corresponding to the stress reverse point, τ_0 is the pile shaft
 175 stress corresponding to the stress reversal point. When p_0 and τ_0 are equal to zero, Eq.(4)
 176 degenerates to the expression of the initial loading curve.

177 Substituting Eqs. (2) and (4) into Eq. (1), the total pile shaft displacement at a given depth
 178 can be expressed as Eq. (5):

$$179 \quad u = p + s = p_0 + \frac{\eta\tau_0 - \tau_u}{\eta G_{s,\max}} \ln \left(1 - \frac{\tau - \tau_0}{\eta(\tau_u - \eta\tau_0)} \right) + \psi\tau \quad (5)$$

180 where $p_0 = u_0 - s_0 = u_0 - \psi\tau_0$, and u_0 denotes the total shaft displacement of the pile
 181 corresponding to the shaft shear stress reversal point. Thus, Eq. (5) can be expressed using Eq.
 182 (4), which is the load transfer function used to simulate the relationship between the pile shaft
 183 resistance and the relative pile-soil displacement.

$$184 \quad u = u_0 + \frac{\eta\tau_0 - \tau_u}{\eta G_{s,\max}} \ln \left(1 - \frac{\tau - \tau_0}{\eta(\tau_u - \eta\tau_0)} \right) + \psi(\tau - \tau_0) \quad (6)$$

185 2.2 Group interaction for energy piles considering ‘sheltering-reinforcing’ effect

186 As discussed in the previous section, the pile-soil-pile interaction in the pile group can be
 187 considered as linearly elastic and suitable for the principle of superposition. According to
 188 previous studies (Randolph and Wroth 1979), for the two energy piles system (i and j)

189 subjected to thermomechanical loading, the vertical elastic displacement of the pile i can be
 190 divided into three parts: (i) the displacement (s_{i0}) induced by its own load; (ii) the displacement
 191 (Δs_{i0}) induced by the ‘sheltering-reinforcing’ effect of pile j ; (iii) the additional displacement
 192 (s_{ij}) caused by j pile under its own load. If the ‘sheltering-reinforcing’ effect is not considered,
 193 the total elastic displacement of i pile can be written as follows:

$$194 \quad s_i = s_{i0} + s_{ij} \quad (7)$$

195 In the proposed method, we consider the ‘sheltering-reinforcing’ effect. Therefore, the total
 196 elastic displacement of i pile can be written as follows:

$$197 \quad s_i = s_{i0} - \Delta s_{i0} + s_{ij} \quad (8)$$

198 According to the formulation proposed by Randolph and Worth (1978), s_{i0} can be
 199 calculated as follows:

$$200 \quad s_{i0} = \frac{\tau_{si} r_0}{G} \ln \frac{r_m}{r_0} \quad (9)$$

201 The shear stress of pile i transferred to the side of pile j can be expressed as follows:

$$202 \quad \tau_{sji} = \frac{\tau_{sij} r_0}{s_{aij}}, (r_0 < s_{aij} < r_m) \quad (10)$$

203 where s_{aij} denotes the distance between the axes of two piles. Considering the ‘sheltering-
 204 reinforcing’ effects of pile j on pile i , Δs_{i0} can be obtained by:

$$205 \quad \Delta s_{i0} = \frac{\tau_{sji} r_0}{G} \ln \frac{r_m}{s_{aij}} = \frac{\tau_{sij} r_0}{s_{aij}} \frac{r_0}{G} \ln \frac{r_m}{s_{aij}} \quad (11)$$

206 If the existence of pile j is not considered, then the displacement at the position of pile j
 207 caused by pile i under its own load is:

$$208 \quad s_{ji0} = \frac{\tau_{sji} r_0}{G} \ln \frac{r_m}{s_{aij}}, (r_0 < s_{aij} < r_m) \quad (12)$$

209 In addition, the shear stress transferred from pile i to the side of pile j (i.e., τ_{sij}) reduces
 210 the displacement of pile j as follows:

$$211 \quad \Delta s_{ji0} = \frac{\tau_{sji} r_0}{G} \ln \frac{r_m}{r_0} = \frac{\tau_{sji} r_0}{s_{ajj} G} \ln \frac{r_m}{r_0} \quad (13)$$

212 Therefore, the additional displacement of pile j induced by the load of pile i can be
213 expressed as follows:

$$214 \quad s_{ji} = s_{ji0} - \Delta s_{ji0} = \frac{\tau_{sji} r_0}{G} \left(\ln \frac{r_m}{s_{ajj}} - \frac{r_0}{s_{ajj}} \ln \frac{r_m}{r_0} \right) \quad (14)$$

215 According to the assumption that $\tau_{sij} = \tau_{sji} = \tau_{si}$ (Zhang et al. 2016), the additional
216 elastic displacement of pile i caused by the load of pile j is equal to the additional elastic
217 displacement of pile j caused by the load of pile i , that is:

$$218 \quad s_{ij} = s_{ji} = \frac{\tau_{si} r_0}{G} \left(\ln \frac{r_m}{s_{ajj}} - \frac{r_0}{s_{ajj}} \ln \frac{r_m}{r_0} \right) \quad (15)$$

219 Thus, for a two-pile system, the total elastic displacement of pile i can be obtained as
220 follows:

$$221 \quad s_i = s_{i0} - \Delta s_{i0} + s_{ij} = \frac{\tau_{si} r_0}{G} \left[\ln \frac{r_m}{r_0} - \frac{r_0}{s_{ajj}} \ln \frac{r_m}{s_{ajj}} + \ln \frac{r_m}{s_{ajj}} - \frac{r_0}{s_{ajj}} \ln \frac{r_m}{r_0} \right] \quad (16)$$

222 For a group of n piles, the total elastic displacement of pile i can be calculated as
223 follows:

$$224 \quad s_i = s_{i0} - \sum_{j=1, j \neq i}^n (\Delta s_{i0} - s_{ij}) = \frac{\tau_{si} r_0}{G} \left[\ln \frac{r_m}{r_0} - \sum_{j=1, j \neq i}^n \left(\frac{r_0}{s_{ajj}} \ln \frac{r_m}{s_{ajj}} - \ln \frac{r_m}{s_{ajj}} + \frac{r_0}{s_{ajj}} \ln \frac{r_m}{r_0} \right) \right] \quad (17)$$

225 Therefore, the total shaft displacement of the energy pile i is:

$$226 \quad u = p + s = u_0 + \frac{\eta \tau_0 - \tau_u}{\eta G_{s \max}} \ln \left(1 - \frac{\tau_{si} - \tau_0}{\eta (\tau_u - \eta \tau_0)} \right) + \psi' (\tau_{si} - \tau_0) \quad (18)$$

227 where ψ' is the pile-pile interaction parameter, which can be written as follows:

$$228 \quad \psi' = \frac{r_0}{G} \left[\ln \frac{r_m}{r_0} - \sum_{j=1, j \neq i}^n \left(\frac{r_0}{s_{ajj}} \ln \frac{r_m}{s_{ajj}} - \ln \frac{r_m}{s_{ajj}} + \frac{r_0}{s_{ajj}} \ln \frac{r_m}{r_0} \right) \right] \quad (19)$$

229 **2.3 Load transfer function at the base of energy pile group**

230 Similar to the definition of the pile-side displacement, the displacement at the pile end is
 231 the sum of the pile-soil relative displacement (i.e., p_p) and the elastic displacement of the soil
 232 at the pile tip (i.e., s_p). It can be written as

233
$$u_p = p_p + s_p \quad (20)$$

234 The pile-soil relative displacement can be simulated using an exponential model (Liu et
 235 al., 2022), which can be calculated as follows:

236
$$\sigma_p = \sigma_{up} \left[1 - \exp\left(-\frac{G_{pmax}}{\sigma_{up}} p_p\right) \right] \quad (21)$$

237 where σ_p is the pile tip resistance, G_{pmax} is the initial stiffness of the pile tip-soil interface;
 238 σ_{up} is the ultimate pile tip resistance.

239 According to the improved Masing rule (Pei et al. 2022), the load transfer function for
 240 simulate the loading-unloading-reloading path of the pile-soil interaction at the pile tip can be
 241 written as

242
$$\sigma_p = \sigma_{p0} + \kappa(\sigma_{up} - \eta\sigma_{p0}) \left[1 - \exp\left(-\kappa \frac{G_{pmax}}{\sigma_{up} - \kappa\sigma_{p0}} (p_p - p_{p0})\right) \right] \quad (22)$$

243 Thus, the pile-soil relative displacement of the energy pile tip can be written as

244
$$p_p = p_{p0} + \frac{\kappa\sigma_{p0} - \sigma_{pu}}{\kappa G_{pmax}} \ln\left(1 - \frac{\sigma_p - \sigma_{p0}}{\kappa(\sigma_{pu} - \kappa\sigma_{p0})}\right) \quad (23)$$

245 where κ denotes the loading and unloading branching judgment factor, $\kappa = -1$ and $\kappa = 1$
 246 represent unloading and reloading conditions, respectively, p_{p0} denotes the relative
 247 displacement of the pile tip and soil corresponding to the stress reversal point, σ_{p0} is the pile
 248 tip resistance corresponding to the stress reversal point. When p_{p0} and σ_{p0} equal zero, Eq.
 249 (22) degenerates to the expression for the initial loading curve.

250 According to Randolph and Wroth (1979), the elastic vertical displacement of the soil
 251 induced by the pile tip resistance can be obtained as

252
$$s_p = \frac{\pi r_0 (1-\nu)}{4G_{soil}} \sigma_p = \lambda \sigma_p \quad (24)$$

253 where λ is the model parameter. According to the studies in (Lin and Dai 2014), the pile-pile
 254 interaction at the pile tip is insignificant. Therefore, the total displacement of the pile tip can be
 255 expressed as follows:

256
$$u_p = p_p + s_p = p_{p0} + \frac{\eta \sigma_{p0} - \sigma_{pu}}{\eta G_{pmax}} \ln \left(1 - \frac{\sigma_p - \sigma_{p0}}{\eta (\sigma_{pu} - \eta \sigma_{p0})} \right) + \lambda \sigma_p \quad (25)$$

257 where $p_{p0} = u_{p0} - s_{p0} = u_{p0} - \lambda \sigma_{p0}$, and u_{p0} denotes the total displacement of the pile tip
 258 corresponding to the pile tip resistance reversal point. Thus, Eq.(25) can be expressed as Eq.(26),
 259 which is the load-transfer function used to simulate the relationship between the pile tip
 260 resistance and the relative pile tip-soil displacement.

261
$$u_p = u_{p0} + \frac{\eta \sigma_{p0} - \sigma_{pu}}{\eta G_{pmax}} \ln \left(1 - \frac{\sigma_p - \sigma_{p0}}{\eta (\sigma_{pu} - \eta \sigma_{p0})} \right) + \lambda (\sigma_p - \sigma_{p0}) \quad (26)$$

262 2.4 Pile-slab-soil interaction for the energy pile group

263 The pile-slab-soil interaction of the energy pile group is simulated using a spring linked to
 264 the pile head during the load transfer method, as adopted by Knellwolf et al. (2011) and Ravera
 265 et al. (2020a). The spring stiffness is calculated by (Randolph 1994, Selvadurai 2013)

266
$$k_n = \frac{E_s \sqrt{B_{slab} L_{slab}}}{(1-\nu_s^2) \rho_0} \quad (27)$$

267 where E_s is Young's modulus of the soil; ν_s is Poisson's ratio of the soil; L_{slab} and B_{slab}
 268 are the length and width of the slab, respectively; and ρ_0 is a coefficient, which can be
 269 evaluated from the dimensions of the slab (Ravera et al. 2020a).

270 2.5 Parameters determination

271 As shown in Fig. 1, the proposed model has four parameters that are calculated as follows:

272 (1) Ultimate shaft resistance τ_u

273 The ultimate shear stress is the stress corresponding to the asymptote of the stress-strain

274 curve, which is obtained by laboratory interface shear tests. If the test data are not available,
 275 the ultimate shear stress can be calculated as follows:

$$276 \quad \tau_u = (1 - \sin \varphi_s) \sigma'_z \tan \delta_s \quad (28)$$

277 where σ'_z is the effective overburden pressure, $\sigma'_z = \gamma'z$ for the homogeneous soil and
 278 $\sigma'_z = \sum_{i=1}^n \gamma'_i z_i$ for the layered soil, where γ' is the effective weight of the soil. δ_s is the
 279 friction angle of the pile-soil interface, which can be expressed by the soil friction angle (φ_s)
 280 as $\delta_s = \tan^{-1} \frac{\sin \varphi_s \cos \varphi_s}{1 + \sin^2 \varphi_s}$ (Pei et al. 2022b).

281 (2) Initial stiffness of the pile-soil interface G_{smax}

282 According to Randolph and Worth (1978), G_{smax} can be obtained as follows:

$$283 \quad G_{smax} = \frac{2G_s}{D \ln \frac{2r_m}{D}} \quad (29)$$

284 where G_s is the soil shear modulus and r_m is the shear influence radius, which is related to
 285 the pile length and soil layer distribution. The value of the shear influence radius increases with
 286 increasing soil depth. It can be expressed by:

$$287 \quad r_m = 2\delta(1 - \nu_s)L \quad (30)$$

288 where δ is the soil shear modulus ratio, ν_s is the Poisson's ratio of the soil, L is the pile
 289 length. For homogeneous soils, the soil shear modulus ratio can be calculated as $\delta = \frac{G_L}{G_L}$,

290 where G_L and G_L are the soil shear modulus at the middle and tip of the pile, respectively.

291 For multilayered nonhomogeneous soils, the soil shear modulus ratio can be calculated as $\delta =$
 292 $\int G_{iz} dz / G_L L$ according to Lee et al. (1993), in which G_{iz} is the shear modulus of the soil
 293 layer and z is the soil depth. According to Wong and Teh (1995), the shear influence radius
 294 should adopt a value in the range of 0.5-2.5L when the length-to-diameter ratio of the pile falls
 295 within the range of 20-100.

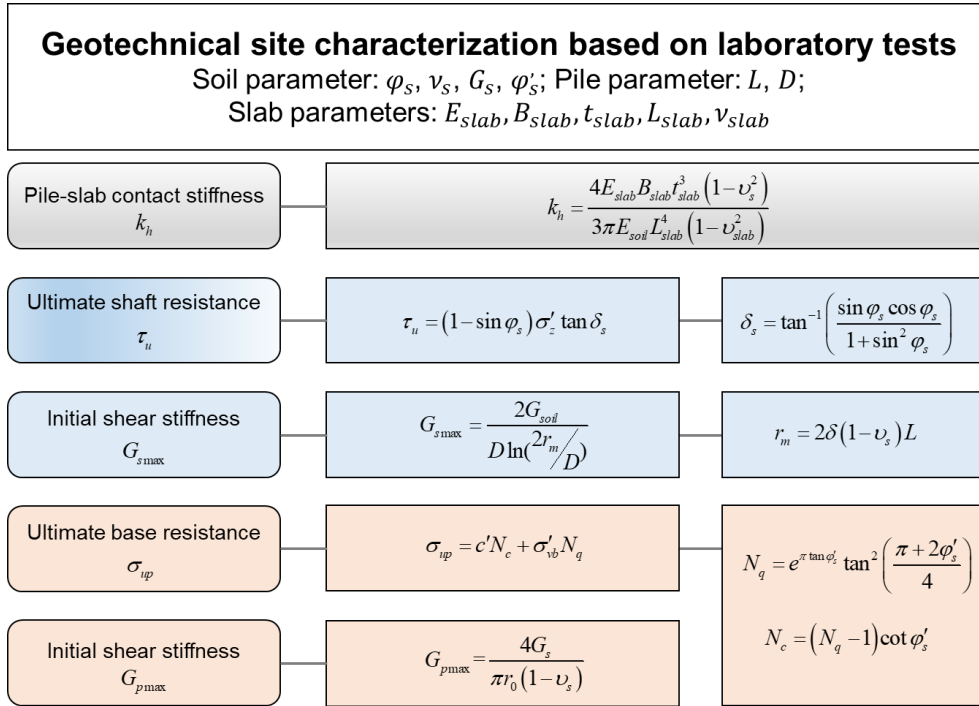
296 (3) Ultimate base resistance σ_{up}

297 σ_{up} can be calculated as $\sigma_{up} = c'N_c + \sigma'_{vb}N_q$, where c' is the effective cohesion of the

298 soil, σ'_{vb} is the effective vertical stress at the pile tip; N_q and N_c are the load capacity
 299 coefficients, which can be calculated by $N_q = e^{\pi \tan \varphi'} \tan^2 \left(\frac{\pi + 2\varphi'}{4} \right)$, $N_c = (N_q - 1) \cot \varphi'$,
 300 where φ' is the effective friction angle of the pile tip soil.

301 (4) Initial shear stiffness of the pile tip G_{pmax}

302 The initial shear stiffness of the pile tip, which can be calculated as $G_{pmax} =$
 303 $\frac{4G_s}{\pi r_0(1 - \nu_s)}$.



304

305

Fig. 1 Steps of calculation for the determination of model parameters

306

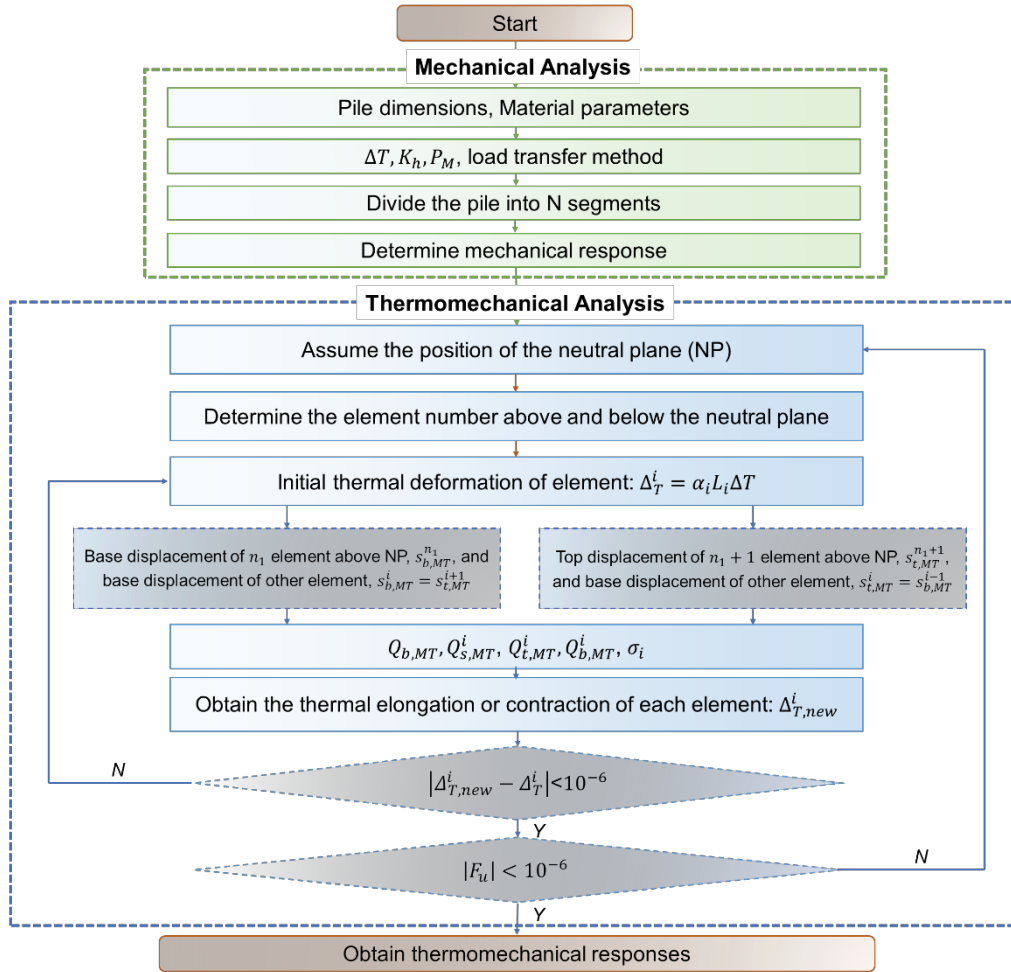
2.6 Implementation for thermomechanical analysis of an energy pile group

307

Approaches such as the one-dimensional element and finite difference methods can
 308 implement the proposed load transfer model. Song and Pei (2022) improved the finite-
 309 difference method proposed by Chen and McCartney (2016), which was divided into
 310 mechanical and thermomechanical analyses, as shown in Fig.2. During the mechanical analysis,
 311 the temperature change is set to zero and the pile is subjected to the mechanical load only.
 312 Besides, no constraint is applied to the pile head since the pile only moves downwards caused
 313 by the mechanical load. The mechanical response could be obtained through an iterative

314 procedure.

315 When the energy pile is subjected to heating/cooling, the pile expands or contracts, a null
316 point (NP) is defined as the position below and above which the pile has opposite displacements.
317 In the thermomechanical analysis stage, the position of the NP should be assumed first, and
318 then the element number above and below the NP should be determined. The displacement
319 calculation of the element below the NP starts from the NP+1 element. Since the displacement
320 of NP caused by the thermal load is zero, the initial displacement of this element is the
321 displacement under the mechanical load. Taking this as the initial element, one iteratively
322 calculates the displacement of all pile elements below the NP and calculates the stress of each
323 element from the pile bottom element upward based on the displacement. The displacement
324 and stress calculation methods for elements above the NP are similar to those below the NP.
325 The difference is that the stress is calculated sequentially from the downward pile head element.
326 The stress at the top of the pile head element is determined by the mechanical load, restraint
327 conditions, and element displacement. The convergence condition of each element under the
328 thermal-mechanical coupling is that the thermal deformation tends to converge (i.e., $|\Delta_{T,new}^i -$
329 $\Delta_{T,old}^i| < 10^{-6}$). At the same time, the position of the assumed NP is adjusted by observing the stress
330 balance of the upper and lower elements on the NP until the positions of the new and old NP
331 reach the convergence condition and the thermomechanical response of all elements of the pile
332 body can be obtained. It should be noted that the load transfer functions of the pile shaft
333 resistance and tip reaction presented in Section 2 are employed during the thermomechanical
334 analysis of the energy pile group in the present study.



Note: ΔT =temperature change; K_h =contact stiffness; P =mechanical load; n =thermal cycles; N =number of pile elements; NP =neutral plane of the pile subjected to thermal loading; Δ_T^i =free thermal deformation of element; α_i =thermal expansion coefficient of the pile; ΔT =temperature change of the pile; $Q_{b,MT}$ = pile tip reaction; $Q_{s,MT}^i$ =side friction of the element subjected to thermal and mechanical loading; $Q_{t,MT}^i$ =thermomechanical top axial stress of the element; $Q_{b,MT}^i$ = thermomechanical base axial stress of the element; σ_i =axial stress of the element; $\Delta_{T,new}^i$ =calculated thermal elongation or contraction of the element; $\sum Q_T^{NP}$ =unbalanced force between the pile above and below the neutral plane.

335

336

Fig. 2 Flow chart for computational thermo-mechanical analysis of energy piles (after Song

337

and Pei 2022)

338 3. Validation of the present model

339 3.1 Tests of an isolated energy pile

340 Guo et al. (2018) reported an energy pile field test conducted at Southeast University,

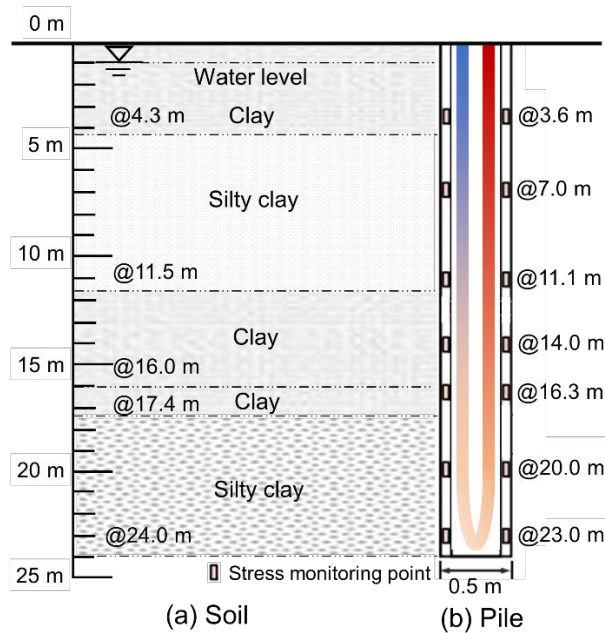
341 Nanjing City, China. The groundwater of the site is located at a depth of 1m. The test pile with

342 a length of 24 m and a diameter of 0.5 m was made of high-strength concrete. The pile was

343 placed in five soil layers, as shown in Fig.3. The top layer of the soil deposit is clay, reaching a

344 depth of 4.3 m. The following layers were silty clay with a thickness of 7.2 m. Below the silty

345 clay, two clay layers were found and reached depths of 16 and 17.4 m, respectively. The last
 346 layer is silty clay with a thickness of 6.6 m, which provides pile tip resistance. Relevant
 347 parameters for the present study were extracted from Guo et al. (2018) and are shown in Table
 348 1. The pile was continuously heated for 168 h at an average power of 3.44 kW. In this study,
 349 the heating durations of 24, 72, 96, and 168 h are selected to be modeled, corresponding to the
 350 pile temperature variations of 11.1, 13.2, 16.6, and 19.3 °C. No mechanical load was imposed
 351 on the pile head during testing, thus the change in pile stress was caused by the thermal load
 352 only. In addition, the contact stiffness between the pile head and superstructure was not
 353 considered in this case study because there were no structural constraints on the top of the pile.



354

355 **Fig. 3** Schematic of the soil and pile referring to the study of Guo et al. (2018)

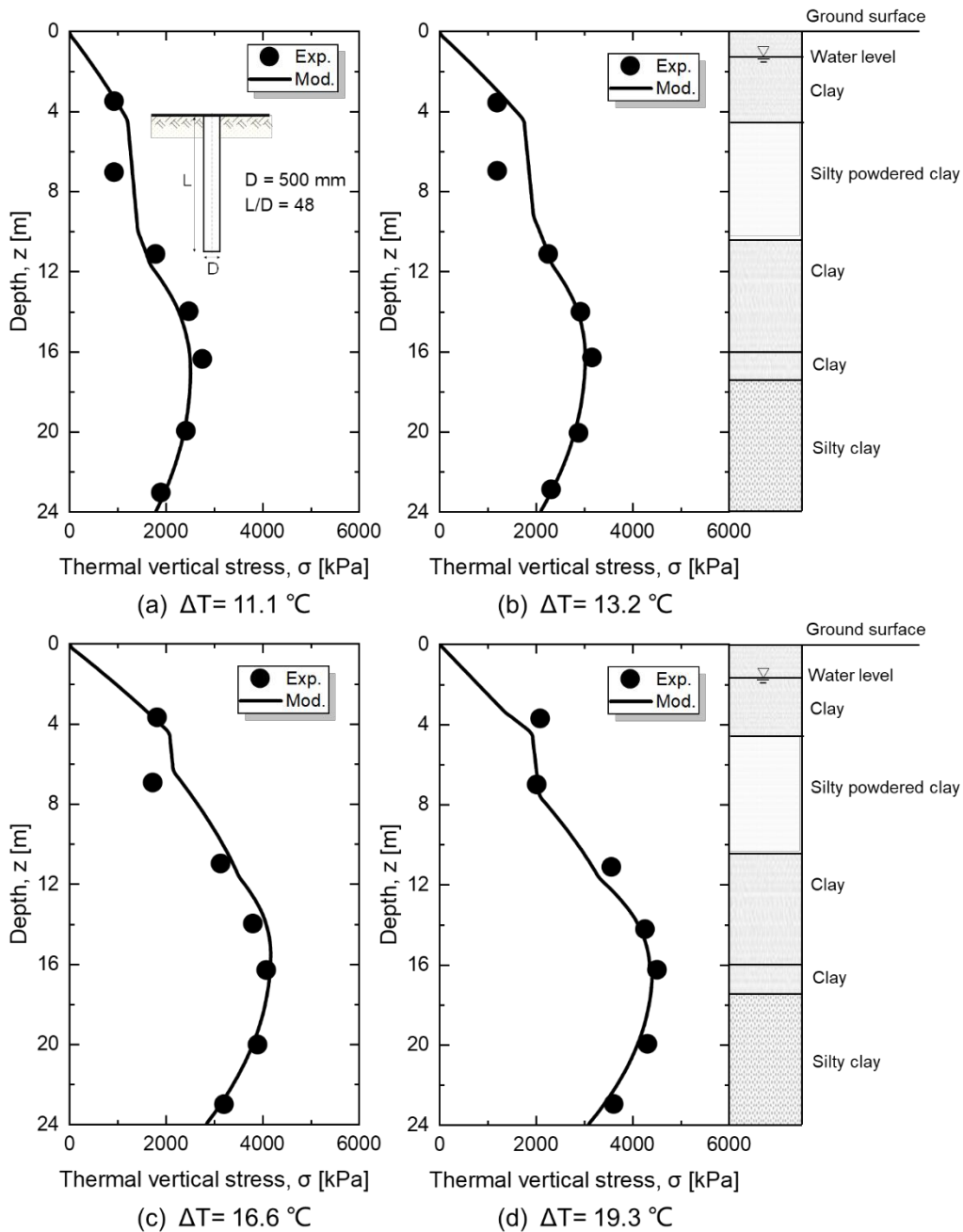
356

Table 1 Soil parameters considered for modelling the field tests of Guo et al. (2018)

Variable	Soil layer, z [m]	Clay [0-4.3]	Silty clay [4.3-11.5]	Clay [11.5-13.5]	Clay [13.5-16]	Silty clay [16-24]	Pile tip [24, -]	Pile
Unit weight, γ_{sat} [kN/m^3]		18.9	17.4	19.7	19.5	19.9	-	24.9
Ultimate skin friction, τ_u [kPa]		2.6	6.5	10.3	22.9	31.9		
Young's modulus, E [MPa]		4.6	3.6	7.5	6.6	7.3	-	45700
Shear modulus, G_{soil} [MPa]		17.1	13.9	28.5	25.2	15.1	-	-
Friction angle, ϕ [$^\circ$]		10	6.6	6.8	18.4	17.3	-	-
Initial stiffness of skin friction, G_{max} [MPa/m]		13.1	11.1	22.9	20.3	11.8	-	-
Ultimate tip resistance, q_b [MPa]		-	-	-	-	-	50	-
Initial stiffness of tip reaction,		-	-	-	-	-	1200	-

$G_{pmax}[MPa/m]$							
Thermal dilation coefficient, $\alpha_s (\mu\epsilon/^\circ\text{C})$	-	-	-	-	-	-	11.6

357 Fig. 4 shows the thermally induced pile axial stresses obtained from the experiments and
358 the model used in this study. A close agreement between the measured and computed values for
359 all the heating steps is observed. The computed thermal stress meaningfully yields a value of
360 zero at the pile head, which reflects the absence of restraint provided by any structural elements.
361 The thermal stress increases with the pile depth and decreases again towards the pile tip.
362 Differences between the simulations and measurements along the pile in the first two soil layers
363 can be found. The reason may be attributed to the significant variations of the ultimate skin
364 friction of the first three soil layers, i.e., 37.82, 12.4 and 106.4 kPa for the first, second and third
365 soil layers, respectively. As the temperature change increases, the second layer of soil needs to
366 mobilize more friction than under lower temperature changes to resist the significantly
367 increased relative pile-soil displacement. Even the third soil layer may mobilize more friction
368 when the second soil layer is incapable of providing enough friction to reach the limit
369 equilibrium, which would induce the stress redistribution along the pile depth and thus explains
370 the variation of the thermal stress of the pile body in the second layer of soil. A similar
371 phenomenon can also be found in previous studies ([Rotta Loria and Laloui 2018](#), [Fang et al.](#)
372 [2020](#)).



373

374 **Fig. 4** Experimental and modeled thermally induced pile axial stresses referring to the tests of
 375 Guo et al. (2018). (a) $\Delta T = 11.1\text{ }^{\circ}\text{C}$; (b) $\Delta T = 13.2\text{ }^{\circ}\text{C}$; (c) $\Delta T = 16.6\text{ }^{\circ}\text{C}$; (d) $\Delta T = 19.3\text{ }^{\circ}\text{C}$

376

377

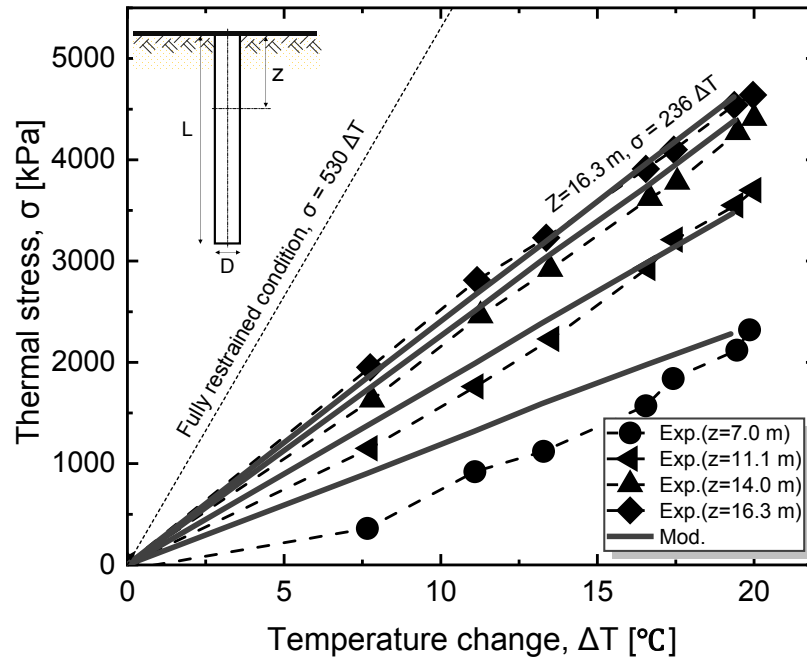
378

379

380

381

Fig. 5 shows the measured and modeled thermal stress at different pile depths versus the average temperature variations of the pile. The computed results capture the overall evolution of the measurements. It can be seen that the computed thermal stress at each depth along the pile has an approximately linear relationship with the temperature change. The maximum thermal stress is at a depth of about 16.3m. The relationship with the average temperature change is $\sigma = 236\Delta T$ kPa.



382

383

Fig. 5 Experimental and modeled thermal stresses at the different pile depths during thermal loading referring to Guo et al.(2018)

384

385 3.2 Tests of an energy pile group

386

387

388

389

390

391

392

393

394

395

396

397

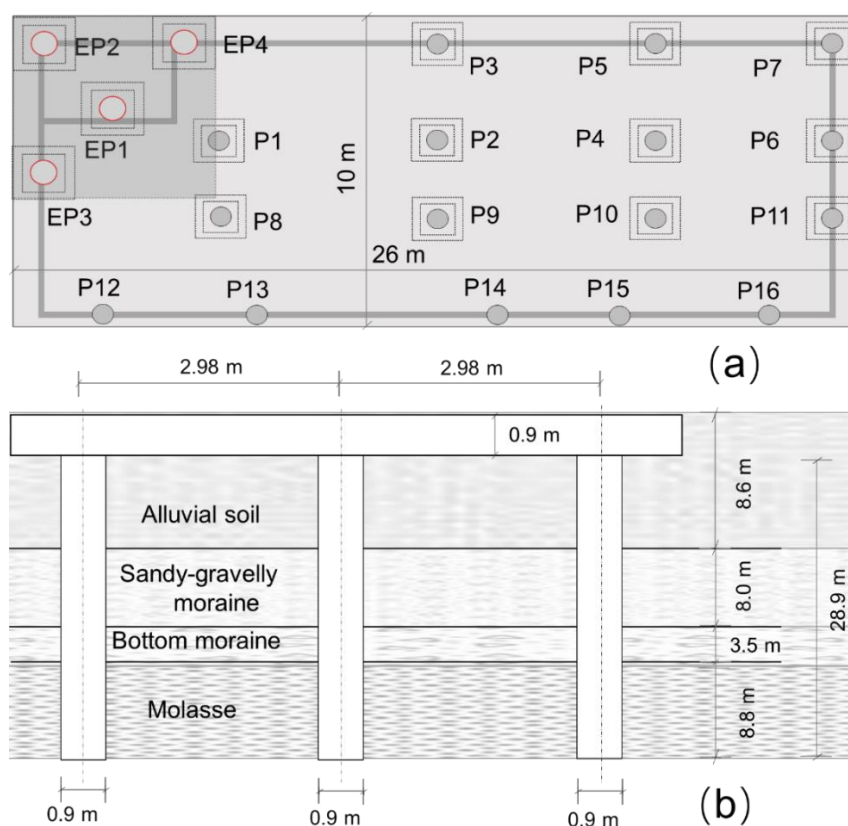
398

399

400

The analysis case was a full-scale field test of a pile group consisting of four energy piles, as reported by Mimouni and Laloui (2015) and Rotta Loria and Laloui (2017, 2018). The energy piles (EP) have a diameter of 0.9 m and a length of 28 m; their arrangement is shown in Fig. 6a. The pile group joint has a slab of 26 m long, 0.9 m thick, and 10 m wide. The piles were placed in five soil layers as shown in Fig 6b. The top layer of the soil deposit was alluvial, reaching a depth of 8.6 m. The subsequent layer is a sandy-gravelly moraine with a thickness of 8 m. Below it, a thin bottom moraine layer is found and reaches a depth of 20.1 m. The last layer is molasses, reaching a depth of 28.9 m. The soil deposit was considered to be fully saturated with water since the groundwater table was located at the surface. The relevant parameters used in this study were extracted from existing studies or calculated according to the determination methods described in Section 2, as shown in Table 2. It is noted that Young's modulus of the Molasse layer provided by Ravera et al. (2020a) was in the range of 3000-7000 MPa, based on which the calculated shear modulus fell in the range of 1153.8 - 2692.3 MPa. The initial stiffness of skin friction and tip reaction of the load transfer in the Molasse layer were calculated according to the equations mentioned in section 2.5 and fell in the range of

401 318.2-742.5 MPa/m and 2176.5-5078.5 MPa/m, respectively. Therefore, this study conducted
 402 two kinds of simulations using the maximum and minimum values of the initial stiffness of skin
 403 friction and tip reaction estimated from the shear modulus. The four energy piles were subjected
 404 to a heating-passive cooling cycle during the test. In this study, the monitoring results of EP1
 405 pile (see Fig.6a) during the heating phase were used to validate the proposed model. The
 406 temperature changes were 5, 10, 15, and 20 °C, respectively. Additionally, an initial vertical
 407 mechanical load of 495 kN was calculated for the single pile tested by Rotta Loria and Laloui
 408 (2017). A contact stiffness calculated as 4450 MPa/m was considered. Besides, thermal stress
 409 means pile vertical stress induced by temperature changes only.



410

411 **Fig.6** Schematic of (a) the energy pile foundation; (b) the soil stratigraphy (modified from

412

[Rotta Loria and Laloui 2017a, 2018a](#))

413

Table 2 Soil and pile parameters considered for modelling the field tests referring to ([Rotta](#)

414

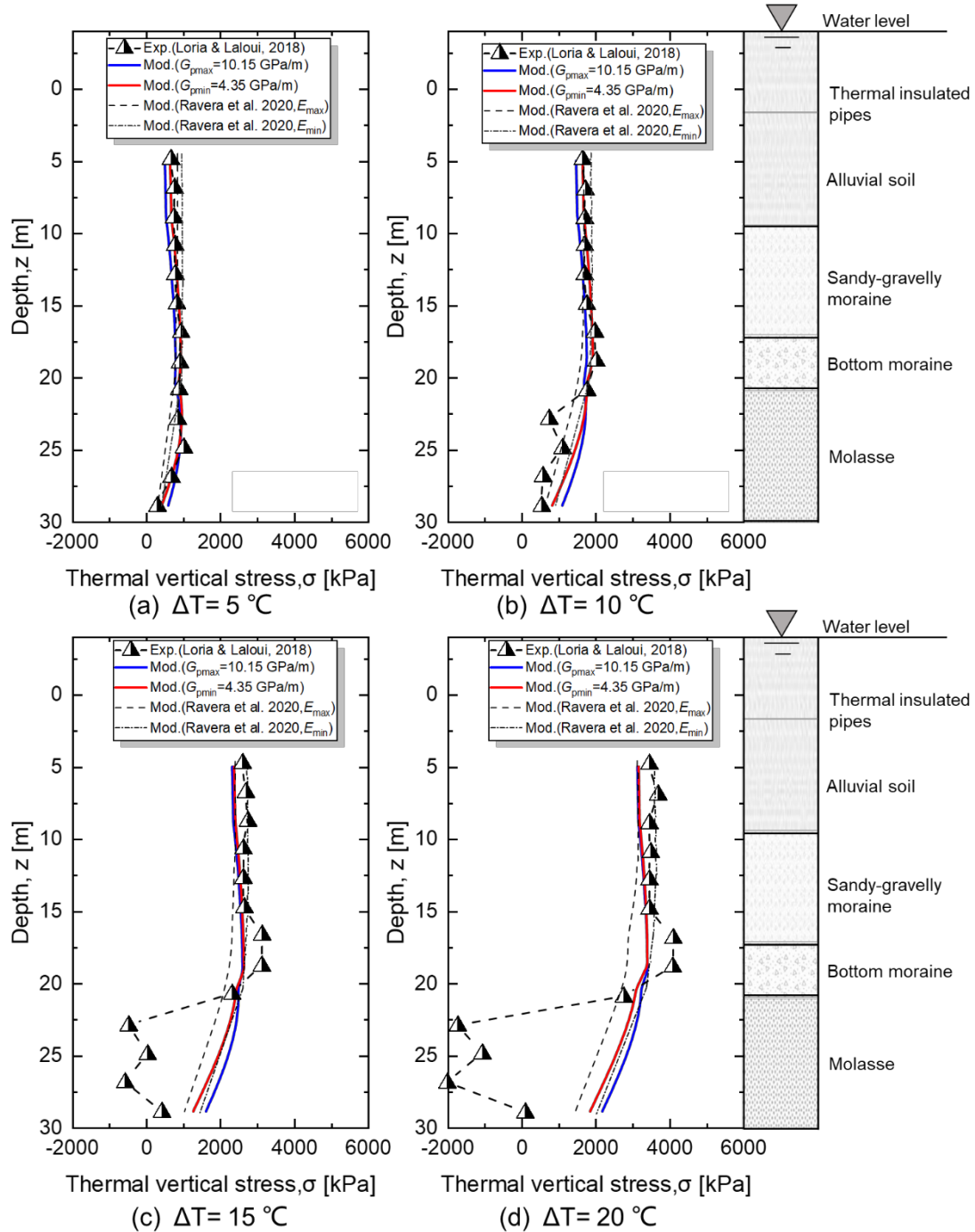
[Loria and Laloui 2017b, Ravera et al. 2020a](#))

Variable \ Soil layer, z [m]	Alluvial soil [0.0, 8.6]	Sandy-gravelly moraine [8.6, 16.6]	Bottom moraine [16.6, 20.1]	Molasse [20.1, 28.9]	Pile tip [24, -]	Pile
Unit weight, γ_{sat} [kN/m ³]	19.8	19	19.8	25.5	-	25

Ultimate skin friction, τ_u [kPa]	7	17	28.9	50.8	-	-
Young's modulus, E [MPa]	5	84	90	3000-7000	-	28000
Shear modulus, G_{soil} [MPa]	2	30	32.1	1153.8 - 2692.3	-	-
Friction angle, φ [°]	30	23	27	35	-	-
Initial stiffness of skin friction, G_{max} [MPa/m]	0.6	8.3	8.9	318.2 - 742.5	-	-
Ultimate tip resistance, q_b [MPa]	-	-	-	-	15.8	-
Initial stiffness of tip reaction, G_{pmax} [MPa/m]	-	-	-	-	2176.5-5078.5	-
Thermal dilation coefficient, α_s ($\mu\epsilon/^\circ\text{C}$)	-	-	-	-	-	10

415 Fig. 7 shows the comparison between experimentally observed and computed thermal
416 vertical stress variations along the pile depth. It is noted that only the measured thermal stress
417 along the pile depth of 4-28 m is presented for comparison because the heat exchange pipes
418 were thermally insulated to a depth of 4 m below the pile heads to eliminate the effects of the
419 climatic conditions on the test results and the temperature changes imposed to the piles in the
420 present simulations were the mean values of the piles at a depth of 4-28 m recorded during the
421 thermal operation (Rotta Loria and Laloui 2017b). It can be seen that the simulated results
422 match well with the experimental results, especially in the lower temperature change operation
423 ($\Delta T = 5$ and 10°C). An increasing difference between the experimental and simulated values of
424 the pile in the molasse layer is found under the higher thermal loads of $\Delta T = 15$ and 20°C . The
425 reason may be attributed to the fact that in the molasse layer, the present method is incapable
426 of capturing the stress redistributions of the pile well under the condition that thermally induced
427 deformation of the soil is more pronounced than that of the piles because the load transfer
428 method used in this study is suitable for the case where the thermally induced deformations of
429 piles govern the performance of energy piles. Similar phenomena and explanations can also be
430 found in studies of Ravera et al.(2020a) and Rotta Loria et al.(2020b). Besides, the simulated
431 results of the model proposed by Ravera et al.(2020a) are also shown for comparison purposes.
432 It can be found that the present model does not need to use experiments or numerical
433 simulations to determine the calculation parameters such as displacement factors and can
434 achieve the same good calculation results as the model of Ravera et al.(2020a). The excellent

435 agreement between the simulated and experimental values of the current model and the
 436 calculated values of other models shows the accuracy of the current model and its promising
 437 potential for simulating thermomechanical responses of an energy pile group.



438
 439 **Fig. 7** Comparison between experimentally observed and computed thermal vertical stresses
 440 variations. (a) $\Delta T = 5^\circ\text{C}$; (b) $\Delta T = 10^\circ\text{C}$; (c) $\Delta T = 15^\circ\text{C}$; (d) $\Delta T = 20^\circ\text{C}$

441 **3.3 FE simulations of energy pile groups**

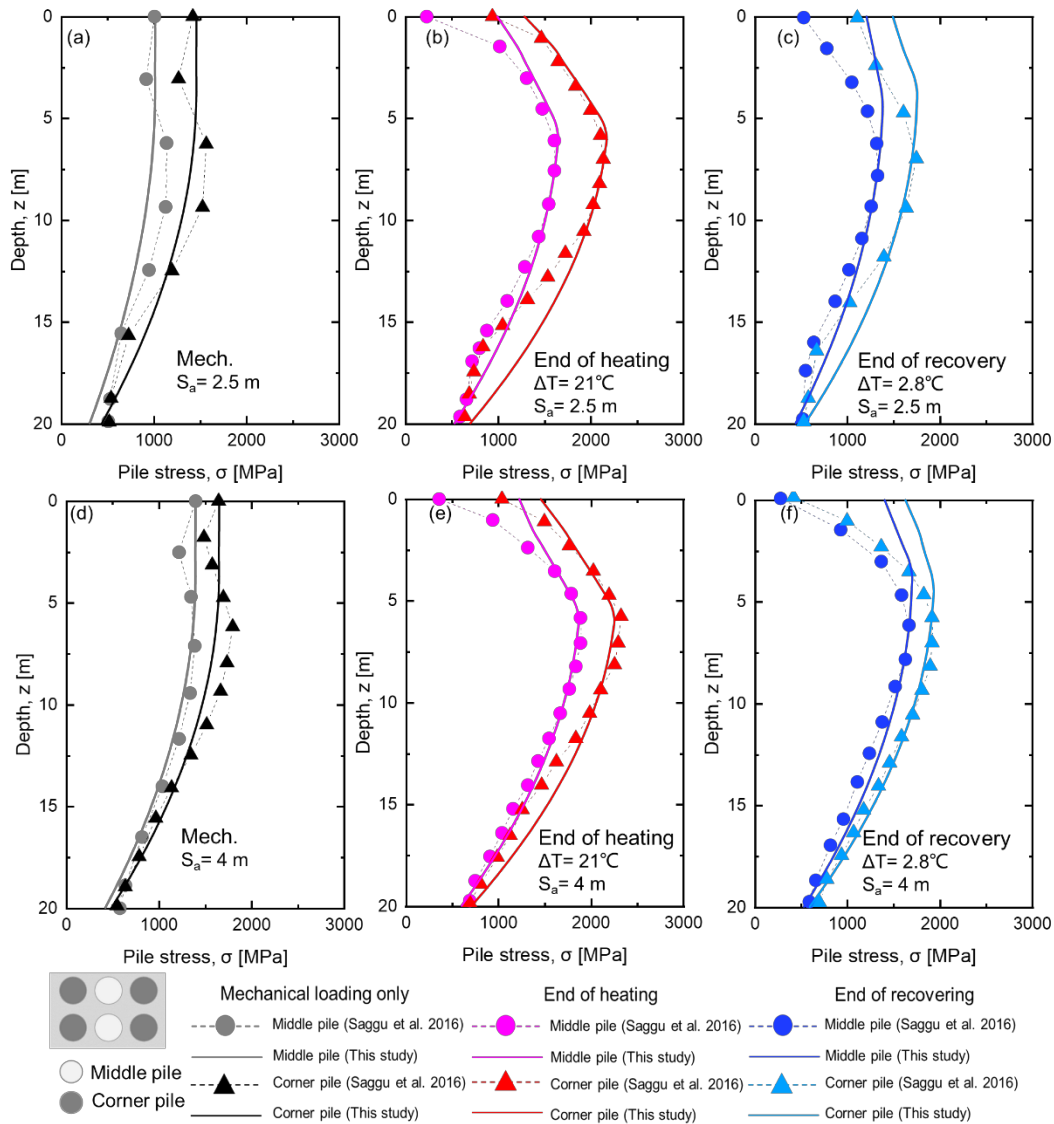
442 Saggiu and Chakraborty (2016) conducted numerical studies of energy pile groups with

443 spacings of 2.5 and 4 m using the finite element software *Abaqus*. In these studies, the pile
 444 group size was 3×2, and the slab was considered to be composed of the same concrete as the
 445 pile. The slabs were 15.5 m long, 1.2 m thick, and 12.9 m wide. All piles, 20 m long and 1 m in
 446 diameter, were wished into a single layer of dry Ottawa sand. During the simulations, an axial
 447 load of 6000 kN was continuously applied to the slab, and all the piles were first heated and
 448 then recovered. The temperature changes were 21 and 2.8 °C at the heating and recovery ends,
 449 respectively. The parameters used in this study are listed in Table 3. A contact stiffness
 450 calculated as 401.7 MPa/m was considered in the study.

451 **Table 3** Soil and pile parameters considered in the present study referring to Saggiu &
 452 Chakraborty (2016)

Variable	Soil layer, z [m]	Ottawa sand [0, 20]	Pile tip [24, -]	Pile
Unit weight, γ [kN/m^3]		18	-	25
Ultimate skin friction, τ_u [kPa]		31.6	-	-
Shear modulus, G_{soil} [MPa]		32.6	-	-
Friction angle, ϕ [$^\circ$]		32	-	-
Initial stiffness of skin friction, G_{max} [MPa/m]		16.2	-	-
Ultimate tip resistance, q_p [MPa]		-	8.3	-
Initial stiffness of tip reaction, G_{pmax} [MPa/m]		-	118.6	-
Young's modulus, E_p (GPa)		-	-	33.7
Thermal dilation coefficient, α_s ($\mu\epsilon/^\circ C$)		-	-	10

453 Fig.8 shows the FE simulated and modeled pile axial stresses, referring to Saggiu and
 454 Chakraborty (2016). Fig.9(a), (b), and (c) show the axial stress in piles with 2.5 m center-to-
 455 center spacing. Close agreement was observed between the FE simulations and the results of
 456 the present model. Under mechanical loading, the pile stress decreases with depth. The axial
 457 stress of the pile significantly increased when the pile temperature change reached 21 °C. The
 458 vertical stress at the end of the recovery phase was slightly higher than that under mechanical
 459 loading, because the pile did not return to the initial temperature. An interesting phenomenon
 460 is that the corner piles show a more significant thermal stress than the central piles because of
 461 the interaction effects, which is in agreement with previous studies (Jeong et al. 2014,
 462 Suryatriyastuti et al. 2016). A similar phenomenon can be observed in Fig.9(d), (e), and (f) for
 463 the piles with 4.0 m center-to-center spacing.



464

465 **Fig. 8** FE simulated and modeled pile axial stresses referring to Saggu & Chakraborty(2016).

466 (a), (b), and (c) are the axial stresses in pile with 2.5 m center-to-center spacing; (d), (e), and

467 (f) are the axial stresses in pile with 4.0 m center-to-center spacing

468 Furthermore, finite element simulations of Rotta Loria and Laloui (2016) were employed

469 for comparison with the simulations of the proposed model in this study to investigate the

470 ‘sheltering-reinforcing’ effect in an energy pile group. The piles in the group had a length of 10

471 m and a diameter of 1 m. Young’s modulus and Poisson’s ratio of the piles were 30 GPa and

472 0.25, respectively. The thermal dilation coefficient of the piles was $10 \mu\epsilon/^\circ\text{C}$. The piles were

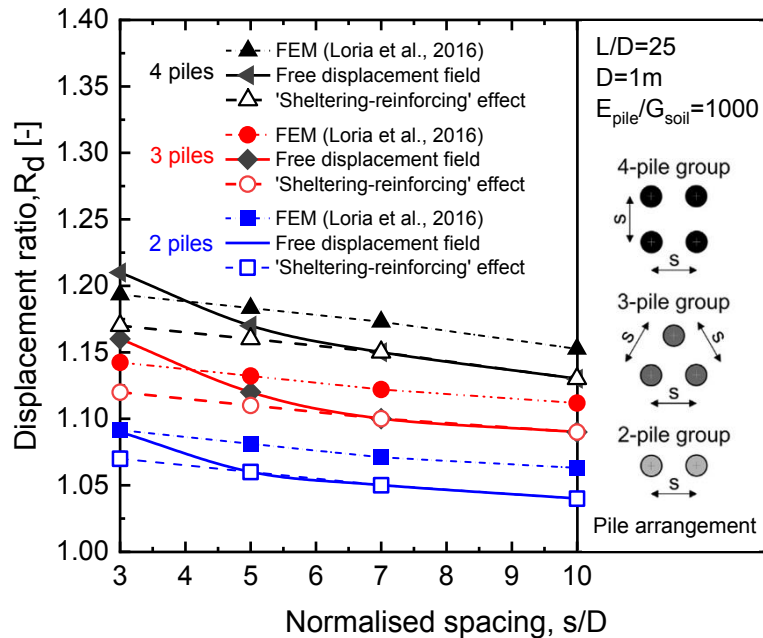
473 sited into homogeneous sand with a shear modulus of 30 MPa and a Poisson’s ratio of 0.3. The

474 temperature change is 10°C during the simulations. The contact stiffness was considered to be

475 zero since the pile head could move freely.

476 Rotta Loria and Laloui (2016) defined the displacement ratio to analyze the displacement
 477 characterizing energy pile group. The displacement ratio is expressed as:

478
$$R_d = \frac{\text{Average displacement of group}}{\text{Displacement of single pile under the same average load}} \quad (31)$$



479
 480 **Fig. 9** Displacement ratio under the different pile spacings

481 Fig.9 shows the displacement ratio for various pile groups under different pile spacings. It
 482 can be seen that there is good agreement between the results of the finite element simulation
 483 and the results obtained by the present method with and without the ‘sheltering-reinforcing’
 484 effect in the group. The difference between the results without and with consideration of the
 485 ‘sheltering-reinforcing’ effect tend to disappear when s/D is larger and the convergence is
 486 delayed if the number of piles increases. The displacement ratio obtained by the finite element
 487 simulation is the largest, and the results without and with consideration of the ‘sheltering-
 488 reinforcing’ effect are smaller and smallest, respectively. The possible reasons, similar to those
 489 discussed by Liu et al. (2022), are as follows:

- 490 (i) The nonlinear interaction of the pile-soil interface is not considered in the finite
 491 element simulations of Rotta Loria and Laloui (2016). Thus, when the pile is
 492 subjected to the thermal load, the pile and soil will deform together, and there is

493 no relative slip between them. However, the nonlinear pile-soil interaction is
 494 considered in the proposed model, which means there will be a relative slip
 495 between the pile and soil. The shaft resistance induced by surrounding soil will
 496 hinder the upward expansion of the pile. Therefore, the displacement ratio
 497 obtained by the finite element simulation is greater than that obtained by the model
 498 proposed in this study.

499 (ii) Even though the nonlinear mechanical properties of the interface have been
 500 considered, the calculation without considering the ‘sheltering-reinforcing’ effect
 501 would overestimate the displacement ratio of the pile.

502 Besides, the displacement ratio obtained in the free displacement field increases significantly
 503 when $s/D=3$. The reason may be that the shear displacement of the surrounding soil in the free
 504 displacement field varies according to a non-linear decreasing function with pile spacing and
 505 increases rapidly at smaller pile spacings (Wang et al., 2016). The comparison results show the
 506 importance of considering the ‘sheltering-reinforcing’ effect in estimating the energy pile group
 507 response and the relevance of the model proposed in the present study.

508 4. Parametric study

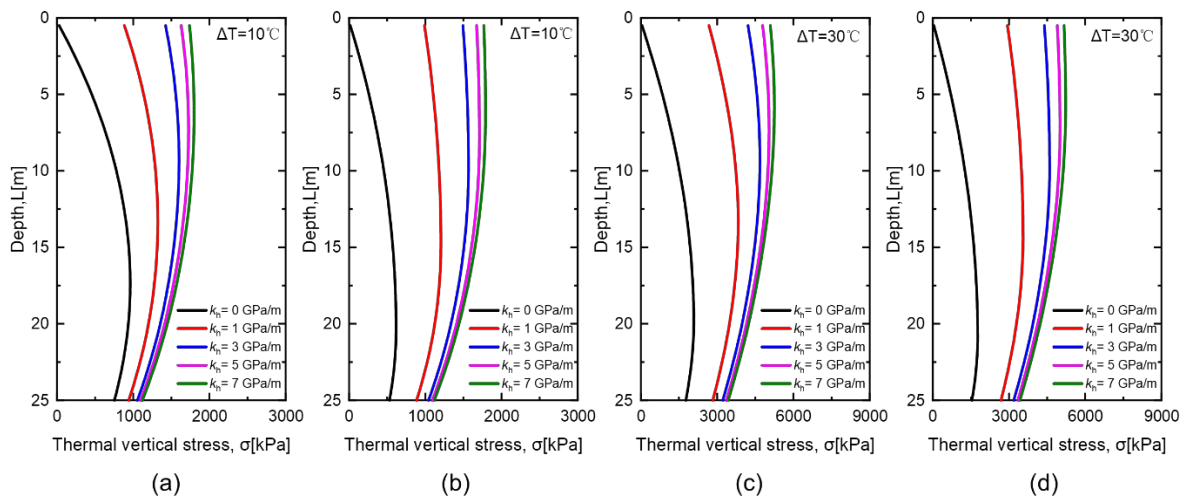
509 This section aims to study the influence of the pile-slab-soil interaction, pile spacing, pile
 510 position and number in a group using the present load transfer model. To this end, a series of
 511 simulations was conducted using the parameters listed in Table 4.

512 **Table 4** Soil and pile parameters considered in the present study

Variable	Value
Length, $L[m]$	25
Pile diameter, $D[m]$	1
Young’s modulus of piles, $E_p (GPa)$	30
Unit weight, $\gamma [kN/m^3]$	19.8
Friction angle, $\varphi [^\circ]$	33
Thermal dilation coefficient of piles, $\alpha_s (\mu\epsilon/^\circ C)$	10
Mechanical load, $P [kN]$	3000
Ultimate skin friction, $\tau_u [kPa]$	40.1
Initial stiffness of skin friction, $G_{s,max}[MPa/m]$	30
Ultimate tip resistance, $\sigma_{up} [MPa]$	10
Initial stiffness of tip reaction, $G_{p,max}[MPa/m]$	1500

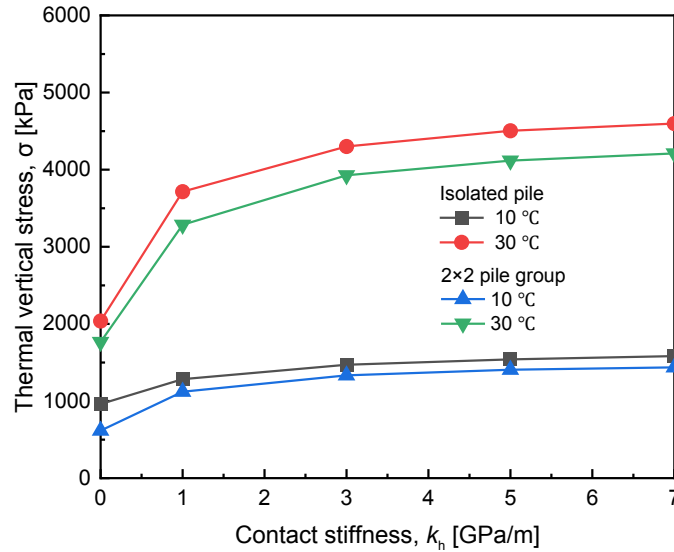
513 **4.1 Effect of the pile-slab-soil interaction**

514 To study the effect of the pile-slab-soil interaction on the thermomechanical behavior of
 515 an energy pile group, a 2×2 pile group and an isolated pile were modeled. The pile-to-pile
 516 spacing of the group was three times the pile diameter. The parameters used in simulations are
 517 shown in Table 4. The piles were subjected to temperature changes of 10 and 30 °C. Contact
 518 stiffness values of 0, 1, 3, 5, and 7 GPa/m were used in simulations. Fig.10 shows the effect of
 519 the contact stiffness on the thermal vertical stress of the pile. It can be observed that more
 520 thermal stress was induced as the contact stiffness increased. The thermal stress generated at
 521 the pile head of the pile group was slightly larger owing to the pile-slab-soil interaction. Fig.11
 522 shows the effect of the contact stiffness on the maximum thermal vertical stress in the pile. It
 523 can be found that the maximum thermal stress in the pile in the group under the same contact
 524 stiffness was smaller than that of the isolated pile. This phenomenon has also been observed in
 525 previous studies (Suryatriyastuti et al. 2016, Ravera et al. 2020a).



526 (a) (b) (c) (d)

527 **Fig. 10** Effect of contact stiffness on the thermal vertical stress of the pile. (a) and (b) are the
 528 thermal vertical stress under a temperature change of 10 °C of an isolated pile and a pile in a
 529 2×2 group, respectively; (c) and (d) are the thermal vertical stress under a temperature change
 530 of 30 °C of an isolated pile and a pile in a 2×2 group



531

532

Fig. 11 Effect of contact stiffness on maximum thermal vertical stress of the pile

533

534

535

536

537

538

539

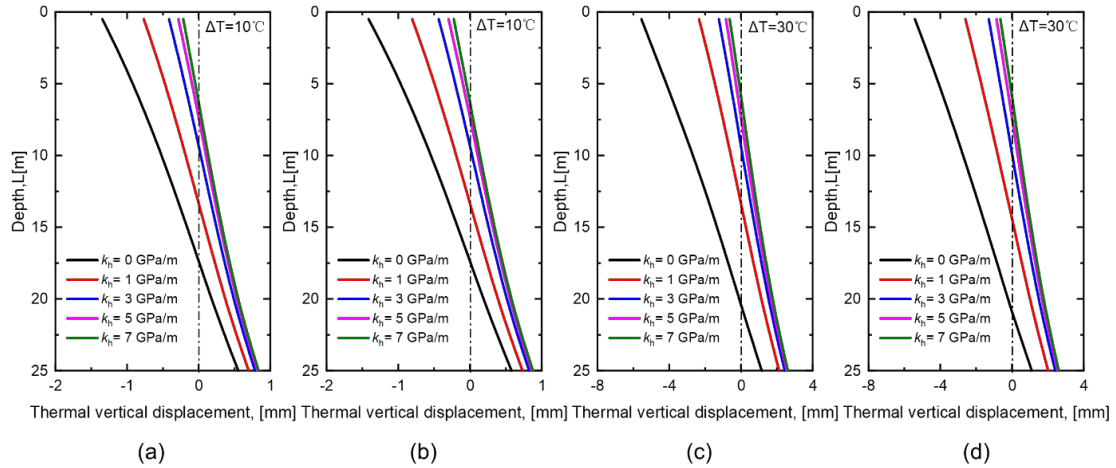
540

541

542

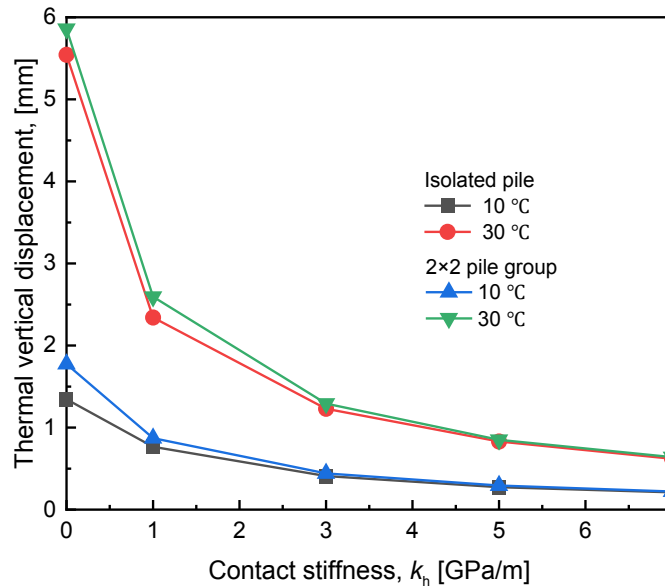
543

The thermally induced downward displacement of the pile under different levels of pile-slab-soil interaction is compared in Fig.12. According to the study of Najma and Sharma (2021), the location of the NP (i.e., thermally induced displacement equal to zero) approaches the pile head with greater pile head constraint, which explains why the position of NP gradually moves upward as the contact stiffness increases. It is also observed that the absolute values of the pile head and end displacements decreased and increased, respectively, as the contact stiffness increased. Additionally, the NP of the pile group was lower than that of the isolated pile under the same constraint conditions. Fig.13 presents the effect of the contact stiffness on the absolute value of the maximum thermal vertical displacement of the pile. Compared with the isolated piles, the pile group had larger thermally induced displacements under the same constraints; however, this difference became insignificant as the temperature change increased.



544

545 **Fig. 12** Effect of the contact stiffness on thermal vertical displacement of the pile. (a) and (b)
 546 are the thermal vertical displacement under a temperature change of 10 °C of an isolated pile
 547 and a pile in a 2×2 group; (c) and (d) are the thermal vertical displacement under a
 548 temperature change of 30 °C of an isolated pile and a pile in a 2×2 group



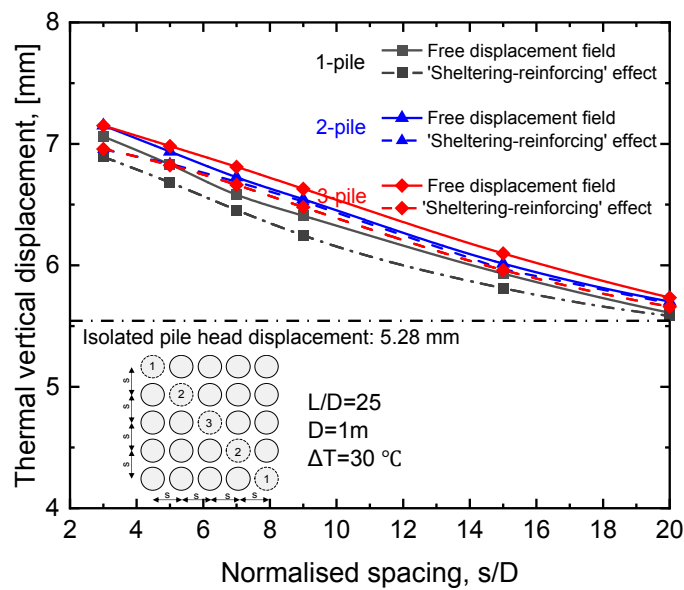
549

550 **Fig. 13** Effect of the contact stiffness on the absolute value of maximum thermal vertical
 551 displacement of the pile

552 **4.2 Effect of the pile spacing**

553 Section 3.3 investigated the effect of pile spacing on a group with 2, 3 and 4 piles. In this
 554 section, the study was extended to a 5×5 pile group. The parameters used in the simulation are
 555 shown in Table 4. The pile-to-pile spacing of the group was three times the pile diameter. During
 556 the simulation, all the group piles were energy piles and subjected to a temperature change of
 557 30 °C. Besides, contact stiffness equal to zero was considered. Fig. 14 shows the vertical thermal

558 displacement of the pile head subjected to different spacings. It can be observed that the thermal
 559 displacements decreased with increasing pile spacing, which is consistent with the results of
 560 Jeong et al. (2014) and Rotta Loria et al. (2016). This may be because an increase in pile spacing
 561 weakens the pile interactions within the group. The mechanism was discussed in detail in a
 562 study by Rotta Loria et al.(2016) on the interaction factor of energy-pile groups. In addition,
 563 the comparison results with and without considering the ‘sheltering-reinforcing’ effect, shown
 564 in Fig.14, further indicate the advantage of the present method in the analysis of the response
 565 of the energy pile group.



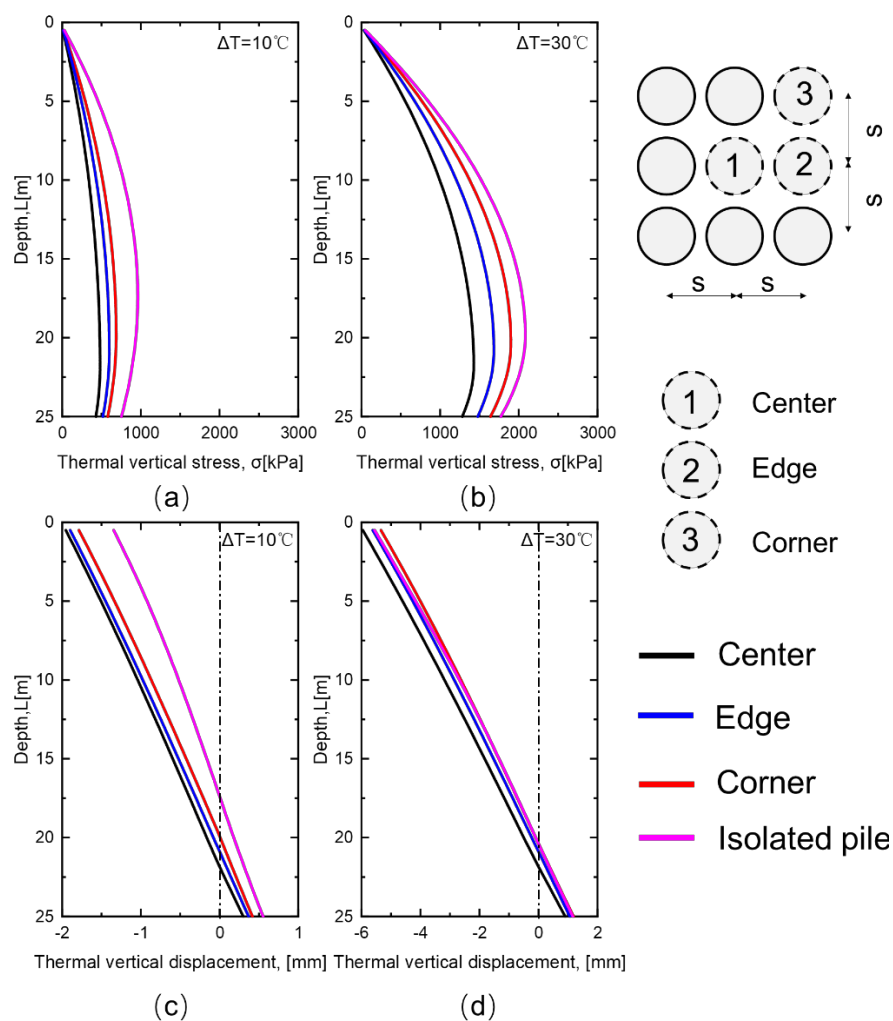
566

567 **Fig. 14** Thermal displacement of the pile head under different pile spacing

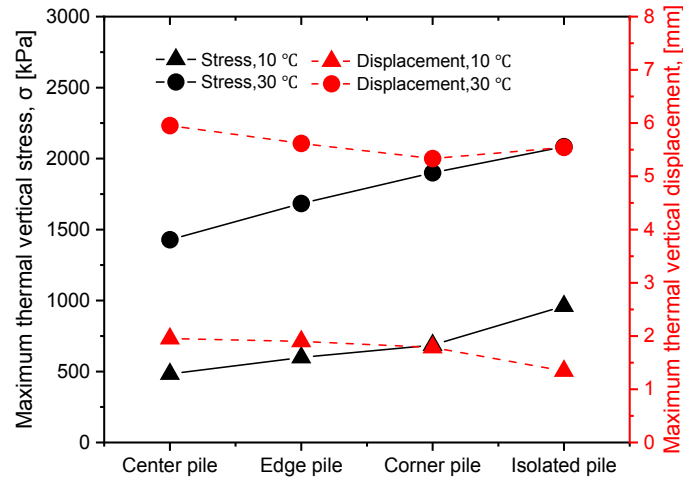
568 **4.3 Effect of pile position in a group**

569 This section aims to study the effect of the pile position in a 3×3 group on the
 570 thermomechanical response. The pile-to-pile spacing of the group was three times the pile
 571 diameter. During the simulation, all the group piles were energy piles and subjected to a
 572 temperature change of 10 and 30 °C. Besides, contact stiffness equal to zero was considered.
 573 Fig.15 shows a comparison of the profiles of the vertical thermal stress and displacement for
 574 the corner, edge, and center energy piles. For the sake of clarity, the effect of pile position in
 575 the group on the maximum thermal vertical stress and displacement of the pile under

576 temperature changes of 10 and 30 °C is summarized in Fig.16. It can be observed that the
 577 maximum and minimum thermal stresses occur at the corner and center piles, respectively,
 578 whereas the minimum and maximum thermal displacements occur at the corner and center piles,
 579 respectively. The position of the NP for the corner and center piles are the highest and lowest,
 580 respectively, which means that the corner piles are more constrained than the center piles in the
 581 group. The results of the energy pile group subjected to thermomechanical loads were in
 582 accordance with those of the energy pile group conducted by Ravera et al. (2020a) and the
 583 conventional pile group performed by Comodromos et al.(2016).



584
 585 **Fig. 15** Effect of pile arrangement in a group. Thermal vertical stress of the pile under (a)
 586 $\Delta T=10\text{ }^{\circ}\text{C}$ and (b) $\Delta T=30\text{ }^{\circ}\text{C}$; thermal vertical displacement of the pile under (c) $\Delta T=10\text{ }^{\circ}\text{C}$; (d)
 587 $\Delta T=30\text{ }^{\circ}\text{C}$

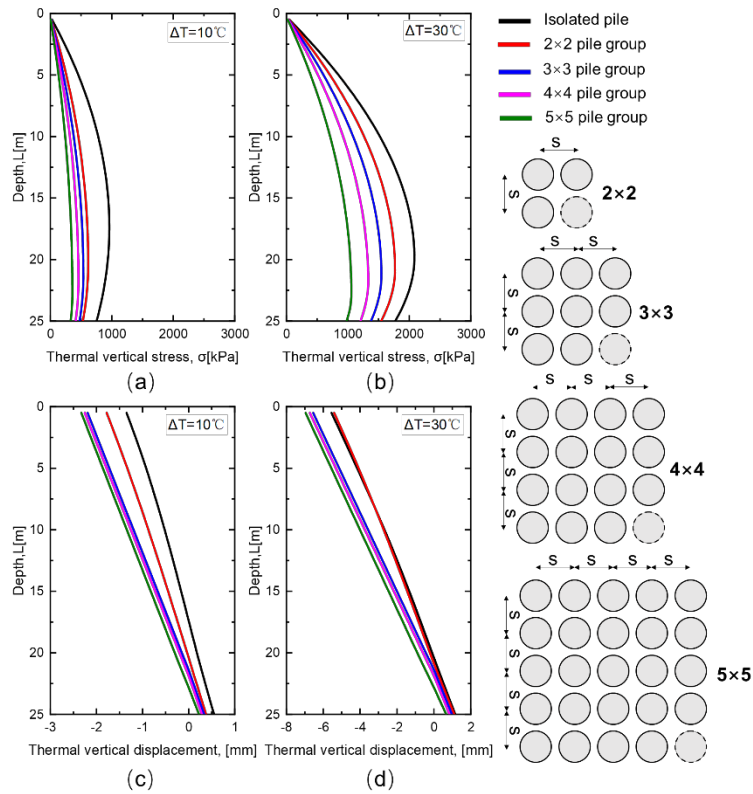


588

589 **Fig. 16** Effect of pile position in the group on the maximum thermal vertical stress and the
 590 absolute value of the displacement of the pile under temperature changes of 10 and 30 °C

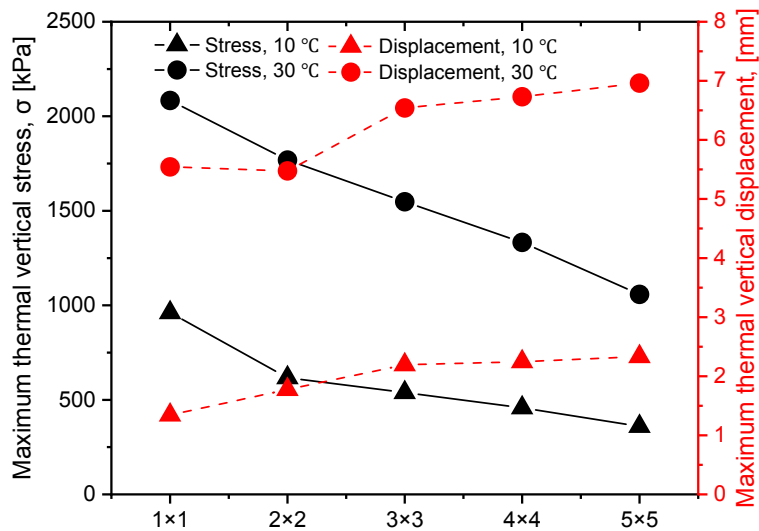
591 **4.4 Effect of the number of piles in the group**

592 This section aims to study the effect of the number of piles in the group on the
 593 thermomechanical response. The pile-to-pile spacing of the group was three times the pile
 594 diameter. During the simulation, all the group piles were energy piles and subjected to a
 595 temperature change of 10 and 30 °C. Besides, contact stiffness equal to zero was considered in
 596 the present case. Fig.17 presents the effect of the number of piles in the group, in which the
 597 thermally induced stress and displacement of an isolated pile (1×1) and 2×2, 3×3, 4×4, and 5×5
 598 pile groups were modeled and compared. For the sake of clarity, the effect of the number of
 599 piles in the group on the maximum thermal vertical stress and the absolute values of the
 600 displacement of the pile under temperature change of 10 and 30 °C is summarized in Fig.18.
 601 The difference between thermal stresses in the pile group and the isolated pile decreased as the
 602 temperature increased. However, the pile head displacement increased with the number of piles.
 603 These results are consistent with those found by experimental and numerical studies (Rotta
 604 Loria and Laloui 2017b, Ravera et al. 2020a, Fang et al. 2022) and validate the applicability of
 605 the present method to simulate the interactions and group effects of energy piles.



606

607 **Fig. 17** Effect of the number of piles in the group. Thermal vertical stress of the pile under (a)
 608 $\Delta T=10\text{ }^\circ\text{C}$ and (b) $\Delta T=30\text{ }^\circ\text{C}$; thermal vertical displacement of the pile under (c) $\Delta T=10\text{ }^\circ\text{C}$; (d)
 609 $\Delta T=30\text{ }^\circ\text{C}$



610

611 **Fig. 18** Effect of the number of the pile in the group on the maximum thermal vertical stress
 612 and the absolute value of the displacement of the pile under temperature changes of 10 and
 613 $30\text{ }^\circ\text{C}$

614 **5. Discussion**

615 In this study, we proposed an experimentally validated load transfer model that considers

616 the ‘sheltering-reinforcing’ effect for the thermomechanical analysis of energy pile groups. The
617 proposed method modeled two well-documented full-scale field tests and two finite-element
618 simulation cases. The comparison results showed that the proposed method could capture
619 several essential aspects of the energy pile group, including thermally induced strain, stress,
620 displacement, and group effects. Also, we conducted a parametric analysis to evaluate the
621 effects of relevant parameters on the thermomechanical behavior of the energy pile group.

622 Recently, several methods considering pile-pile interactions have been developed for the
623 thermomechanical analysis of energy pile groups. For example, Rotta Loria and Laloui (2018)
624 proposed an analytical model to analyze the vertical displacement and the increased
625 deformation of energy pile groups subjected to thermal loads more comprehensively by
626 defining a pile-soil-pile interaction factor. Iodice et al. (2021) provided a unified methodology
627 involving a novel explicit formula for evaluating the maximum thermally induced axial load by
628 establishing the effect of the actual restraint condition at the pile head as a function of the
629 stiffness ratio between the inactive and the active pile subgroups. Nevertheless, the present
630 study is different from the above studies. First, the present study aims to provide an
631 experimentally validated simple load transfer model that considers the ‘sheltering-reinforcing’
632 effects for thermomechanical analysis of energy pile groups. The model can estimate all the
633 thermomechanical behavior of energy pile groups involving vertical displacement, strain, stress,
634 side friction, and group effects. This aim is very different from Rotta Loria and Laloui (2018)
635 study, which mainly focuses on estimating the vertical displacement of the energy pile group.
636 Furthermore, this study developed the load transfer method for the single energy pile under
637 thermomechanical loading by considering the pile-pile interaction in the group to make it
638 suitable for the thermomechanical behavior of energy pile groups. This is different from the

639 study of Iodice et al. (2021) because they fulfilled their aim by analyzing numerical simulation
640 results and proposed the design procedure by using analytical solutions, which can be worked
641 out to obtain explicit formulae for the direct computation of axial force in a multilayer soil.
642 Their practical method is more geared toward calculating the thermomechanical responses of
643 single energy piles. Second, The present study considers both nonlinear pile-soil interaction
644 and elastic deformation of the surrounding soil. The surrounding soil is divided into disturbed
645 and undisturbed zones. The soil in the disturbed zone is a skinny layer of soil on the soil/pile
646 interface. The nonlinearity of the pile-soil interaction was concentrated in this interface. The
647 area outside the interface is the undisturbed zone. Because this zone is subjected to a relatively
648 low stress change, the stress-strain behavior of the soil is mainly elastic. The pile-soil-pile
649 interaction in the pile group is considered linearly elastic and suitable for the principle of
650 superposition. The advantage of this approach is that it can consider the relative slip between
651 piles and soil for the single pile and the interaction between piles-soil-pile in pile groups. Thus,
652 the consideration of pile-soil-pile interaction in the present study is very different from the two
653 studies(Rotta Loria & Laloui, 2018; Iodice et al., 2021).

654 One of basic assumptions of the simple load transfer method is that the mechanical behavior
655 of the energy pile is governed by thermally induced pile axial deformation. Thus, the radial
656 deformation induced by thermal loading is not considered in the present study. There is
657 controversy about whether the influence of radial deformation of energy piles on the response
658 of piles can be ignored in the study of simplified analysis methods. Wang et al. (2015) and
659 Faizal et al.(2018) showed that axial thermal strains were more restricted to thermal expansion
660 than radial thermal strains, which indicated that the radial thermal strains are closer to that of
661 the pile in free thermal expansion. On the contrary, the study by Mimouni and Laloui (2015)
662 showed that the radial thermal strains of the pile were much lower than the free thermal strains,

663 indicating that stiffer soils provided higher restriction to radial thermal strains than the case
664 reported by Wang et al. (2015) and Faizal et al. (2018). It suggests that building loads could
665 affect the development of radial thermal strains along the pile length. Saggiu et al. (2015)
666 observed that the radial strains induced in a pile due to thermo-mechanical loading are higher
667 than that induced due to only mechanical loading. Elzeiny & Suleimam (2021) pointed out that
668 the horizontal pressure decreased by 2~5 kPa when colling the pile, which corresponds quite
669 well with the average stress associated with the measured reduction in pull-out capacity.
670 Bourne-Webb et al. (2022) conducted numerical simulations and comprehensively investigated
671 the problem. They reported that the horizontal stress changes induced by thermal loading have
672 significant potential effects on the thermomechanical behavior of energy piles. The effects
673 depend on the margin concerning the initial mobilization of the shaft resistance by the
674 mechanical load. In summary, the studies mentioned above suggested that the horizontal
675 thermally induced contact stresses would significantly influence the thermomechanical
676 behavior of energy piles because of the radial expansion and contraction of the pile under
677 heating and cooling.

678 However, these require a confirmation from field tests under building loads representing
679 actual boundary conditions. It is noted that the existing studies have different opinions. Olgun
680 et al. (2014) reported that radial contact pressures typically increase less than 15 kPa, which
681 cannot fully explain the shaft resistance observed in heating tests. They thought that the increase
682 of heat exchanger pile capacity in response to heating, observed in several small-scale
683 laboratory studies, cannot be directly attributed to the increase of contact pressure at the soil/pile
684 interface. Faizal et al. (2019) conducted a field test of the energy pile and found that the
685 magnitudes of the axial thermal strains were more constrained than the radial thermal strains at
686 all depths, leading to the development of axial and radial thermal stresses of up to -4.5 and $-$
687 0.015 MPa, respectively, for a change in average pile temperature of 24.1 °C. The magnitudes
688 of the radial thermal stresses with changes in pile temperature were significantly lower than the
689 axial thermal stresses at all depths of the pile, indicating that the radial thermal expansion had

690 negligible effects on the development of axial thermal strains and stresses.

691 In some studies ([Garbellini and Laloui 2019b](#), [Iodice et al. 2020, 2023](#), [Liu et al. 2022](#)),
692 radial thermal effects are commonly considered relatively small compared to axial thermal
693 effects when predicting the axial thermal response of energy piles due to the low diameter-to-
694 length ratio of the pile. Some load transfer analysis methods have consistently validated and
695 predicted the axial thermal response of field- and centrifuge-scale energy piles by neglecting
696 the radial thermal effects ([Knellwolf et al. 2011](#), [Suryatriyastuti et al. 2014](#), [Chen and](#)
697 [McCartney 2016](#), [Luo and Hu 2019](#), [Ravera et al. 2020a](#), [Rotta Loria et al. 2020a](#), [Hu and Luo](#)
698 [2020](#), [Najma and Sharma 2021](#), [Fei et al. 2022](#)). Some numerical studies have also noted that
699 radial thermal stresses in the energy pile are significantly low compared to the axial thermal
700 stresses along the length of the pile ([Ozudogru et al. 2015](#), [Gawecka et al. 2017](#)). Besides,
701 preliminary numerical and analytical studies on energy piles ([Olgun et al. 2014](#), [Zhou et al.](#)
702 [2016](#)), along with a field study on an energy pile without end restraints ([Faizal et al. 2018](#)) have
703 used cavity expansion analyses to confirm that no significant changes in pile–soil contact
704 stresses are expected from the radial thermal expansion of the pile. However, these also need
705 validation at various depths of a field-scale energy pile under building loads.

706 In the present study, a simple load transfer method was proposed for analyzing the
707 thermomechanical behavior of energy pile groups. Therefore, the same assumption adopted by
708 some studies, including the load transfer method for the thermomechanical analysis of energy
709 pile and energy pile groups ([Knellwolf et al. 2011](#), [Suryatriyastuti et al. 2014](#), [Chen and](#)
710 [McCartney 2016](#), [Luo and Hu 2019](#), [Ravera et al. 2020a](#), [Rotta Loria et al. 2020a](#), [Hu and Luo](#)
711 [2020](#), [Najma and Sharma 2021](#), [Fei et al. 2022](#)) is employed to reduce the complexity of coupled
712 thermomechanical analysis.

713 During the development of the simple load transfer model, the shear radius proposed by
714 Randolph and Wroth ([1978](#)) is employed to calculate the initial stiffness of the pile-soil
715 interface, as shown in Eq.(30). The shear radius is affected by pile length, shear modulus and
716 Poisson's ratio of the soil. For the pile under pure mechanical loads, the shear radius has been

717 found to be almost constant with pile depth and more significant than the pile length. However,
718 when the pile was subjected to thermal loads, Rotta Loria and Laloui (2018) conducted finite
719 element simulations and found that the shear radius was not constant with the pile depth and
720 smaller than the pile length. In this study, the calculation of the shear radius is considered in a
721 simplified method. For the multi-layered soil, the shear modulus and Poisson's ratio of each
722 soil layer are different, which means there will be different values of shear radius for each soil
723 layer. Thus, the calculated shear radius varies with pile depth but remains unchanged within the
724 same soil layer through this simplified method. The simplified method mentioned above for the
725 homogeneous soil will fail to obtain a shear radius varying with depth. The calculated shear
726 radius remains unchanged within all the pile depths because the shear modulus and Poisson's
727 ratio of the soil keep constant, which may adversely affect the application of the proposed
728 simple load transfer method for energy pile groups in the homogeneous soil. Furthermore, the
729 shear radius is greater than the pile length under mechanical loads and generally smaller than
730 the pile length under thermal loads (Randolph & Wroth, 1978; Rotta Loria & Laloui, 2018).

731 The proposed simple load transfer method for energy pile groups in the presented study can
732 consider the combined thermal and mechanical loads. During the thermomechanical analysis,
733 it is necessary to consider the shear radius induced by both mechanical and thermal loads.
734 Therefore, the shear radius induced by mechanical loads is employed for the thermomechanical
735 analysis because the radius induced by mechanical loads is much greater than that induced by
736 thermal loads.

737 **6. Conclusions**

738 We proposed a simple load transfer method for the thermomechanical analysis of an energy
739 pile group subjected to thermomechanical loads. The proposed method was validated using
740 full-scale field tests and finite element numerical simulations. In addition, a numerical analysis
741 was performed to evaluate the effects of relevant parameters on the thermomechanical behavior
742 of energy pile groups. The main conclusions are as follows:

743 (1) The results obtained with the proposed method were compared with those from full-
744 scale field tests and FE simulations. The comparison indicated that the proposed model could
745 capture the thermal strain, stress, and displacement of the energy piles in the group under
746 thermal and mechanical loads.

747 (2) Under the same constraints and thermal loads, the energy piles in the group exhibited
748 less thermal stress and larger thermal displacement than the isolated piles. The difference in the
749 thermal stress and displacement between the single energy pile and the energy pile in groups
750 increases with the temperature change increases.

751 (3) The maximum and minimum thermal stresses occurred at the corner and center piles,
752 whereas the minimum and maximum thermal displacements occurred at the corner and center
753 piles, respectively. In addition, the thermal displacement decreased with increasing pile spacing.

754 (4) The thermal stress decreased as the number of energy piles in the group increased under
755 the same thermal load. The difference between thermal stresses in the pile group and the isolated
756 pile decreased as the temperature change increased.

757 **Acknowledgments**

758 This research was supported by the National Natural Science Foundation of China (Grant
759 Nos. 52122805 and 52078103) and the China Scholarship Council (CSC) (Grant No.
760 202106060093).

761 **List of notations**

762	B_{slab}	width of the slab
763	c'	effective cohesion of the soil
764	D	diameter of the pile
765	E_p	Young's modulus of the pile
766	E_{soil}	Young's modulus of the soil
767	G	shear modulus of the soil
768	$G_{s,\text{max}}$	initial stiffness of the pile-soil interface
769	$G_{p,\text{max}}$	initial stiffness of the pile tip-soil interface
770	G_s	soil shear modulus
771	$G_{L/2}$	soil shear modulus at the middle of the pile
772	G_L	soil shear modulus at the tip of the pile

773	K_h	contact stiffness between the pile head and slab
774	L	length of the pile
775	L_{slab}	length of the slab
776	N_q	load capacity coefficients
777	N_c	load capacity coefficients
778	P	mechanical load applied to the pile head
779	p	pile-soil relative displacement
780	p_0	relative pile-soil displacement corresponding to the stress reversal point
781	p_p	pile-soil relative displacement of the pile tip
782	p_{p0}	relative displacement of the pile tip and soil corresponding to the stress reverse point
783	r_0	pile radius
784	r_m	shear influence radius
785	s	elastic displacement of the surrounding soil
786	s_{i0}	displacement of pile i induced by its own load
787	s_{ij}	additional displacement caused by j pile under its own load
788	s_{aij}	distance between the axes of two piles
789	s_p	elastic displacement of the soil at the pile tip
790	u	total shaft displacement at a certain pile depth
791	u_0	total pile shaft displacement corresponding to the shaft shear stress reversal point
792	α_s	thermal dilation coefficient of the pile
793	Δs_{i0}	displacement induced by the ‘sheltering-reinforcing’ effects of pile j
794	δ	soil shear modulus ratio
795	δ_s	friction angle of the pile-soil interface
796	η	loading and unloading branching judgment factor
797	κ	loading and unloading branching judgment factor
798	ν_{soil}	Poisson’s ratio of the soil
799	σ_p	pile tip resistance
800	σ_{up}	ultimate pile tip resistance
801	σ_{p0}	pile tip resistance corresponding to the stress reversal point
802	σ'_{vb}	effective vertical stress at the pile tip
803	σ'_z	effective overburden pressure
804	τ	pile shaft shear stress
805	τ_u	ultimate shear stress
806	τ_0	pile shaft stress corresponding to the stress reverse point
807	φ_s	friction angle of the soil
808	φ'	effective friction angle of the pile tip soil

809 Reference

- 810 Arzanfudi, M.M., Al-Khoury, R., Sluys, L.J., and Schreppers, G.M.A. 2020. A thermo-hydro-
811 mechanical model for energy piles under cyclic thermal loading. *Computers and*
812 *Geotechnics*, **125**(July): 103560. Elsevier. doi:10.1016/j.compgeo.2020.103560.
- 813 Bourne-Webb, P.J., Amatya, B., Soga, K., Amis, T., Davidson, C., and Payne, P. 2009.
814 Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects
815 of pile response to heat cycles. *Géotechnique*, **59**(3): 237–248.
816 doi:10.1680/geot.2009.59.3.237.
- 817 Bourne-Webb, P.J., and Bodas Freitas, T.M. 2020. Thermally-activated piles and pile groups
818 under monotonic and cyclic thermal loading—A review. *Renewable Energy*, **147**: 2572–
819 2581. Elsevier Ltd. doi:10.1016/j.renene.2018.11.025.

- 820 Bourne-Webb, P.J., Lupattelli, A., Freitas, T.M.B., and Salciarini, D. 2022. The influence of
821 initial shaft resistance mobilisation in the response of seasonally, thermally-activated
822 pile foundations in granular media. *Geomechanics for Energy and the Environment*, **32**:
823 100299. Elsevier.
- 824 Caputo, V. 1984. Pile foundation analysis: a simple approach to nonlinearity effects. *Rivista
825 Italiana di Geotecnica*, **18**(1): 32–51.
- 826 Chen, D., and McCartney, J.S. 2016. Parameters for Load Transfer Analysis of Energy Piles
827 in Uniform Nonplastic Soils. *International Journal of Geomechanics*, **17**(7): 04016159.
828 doi:10.1061/(asce)gm.1943-5622.0000873.
- 829 Chen, D., and McCartney, J.S. 2017. Parameters for Load Transfer Analysis of Energy Piles
830 in Uniform Nonplastic Soils. *International Journal of Geomechanics*, **17**(7): 04016159.
831 doi:10.1061/(ASCE)GM.1943-5622.0000873.
- 832 Comodromos, E.M., Papadopoulou, M.C., and Laloui, L. 2016. Contribution to the design
833 methodologies of piled raft foundations under combined loadings. *Canadian
834 Geotechnical Journal*, **53**(4): 559–577. doi:10.1139/cgj-2015-0251.
- 835 Cui, C., Meng, K., Xu, C., Liang, Z., Li, H., and Pei, H. 2021. Analytical solution for
836 longitudinal vibration of a floating pile in saturated porous media based on a fictitious
837 saturated soil pile model. *Computers and Geotechnics*, **131**: 103942. Elsevier.
838 doi:10.1016/j.compgeo.2020.103942.
- 839 Elzeiny, R., and Suleiman, M.T. 2021. Pull-Out Response of a Laboratory-Scale Energy Pile
840 Subjected to Cooling Cycles. *Journal of Geotechnical and Geoenvironmental
841 Engineering*, **147**(7): 4021044. American Society of Civil Engineers.
- 842 Faizal, M., Bouazza, A., Haberfield, C., and McCartney, J.S. 2018. Axial and radial thermal
843 responses of a field-scale energy pile under monotonic and cyclic temperature changes.
844 *Journal of Geotechnical and Geoenvironmental Engineering*, **144**(10): 4018072.
845 American Society of Civil Engineers.
- 846 Faizal, M., Bouazza, A., McCartney, J.S., and Haberfield, C. 2019. Axial and radial thermal
847 responses of energy pile under six storey residential building. *Canadian Geotechnical
848 Journal*, **56**(7): 1019–1033. doi:10.1139/cgj-2018-0246.
- 849 Fang, J., Kong, G., Meng, Y., Wang, L., and Yang, Q. 2020. Thermomechanical Behavior of
850 Energy Piles and Interactions within Energy Pile–Raft Foundations. *Journal of
851 Geotechnical and Geoenvironmental Engineering*, **146**(9): 04020079.
852 doi:10.1061/(asce)gt.1943-5606.0002333.
- 853 Fang, J., Kong, G., and Yang, Q. 2022. Group Performance of Energy Piles under Cyclic and
854 Variable Thermal Loading. *Journal of Geotechnical and Geoenvironmental Engineering*,
855 **148**(8): 1–10. doi:10.1061/(ASCE)GT.1943-5606.0002840.
- 856 Fei, K., Ding, S.-J., and Qin, H.-Y. 2022. Analysis of energy pile groups subjected to non-
857 uniform thermal loadings. *Underground Space*,. Tongji University.
858 doi:10.1016/j.undsp.2022.05.003.
- 859 Fei, K., Zhu, Z.H., Shi, Y.H., and Zhou, Y. 2020. A simplified method for geotechnical
860 analysis of energy pile groups. *Yantu Lixue/Rock and Soil Mechanics*, **41**(12): 3889–
861 3898. doi:10.16285/j.rsm.2020.0313.
- 862 Frank, R. 1982. Estimation par les paramètres pressiométriques de l'enfoncement sous charge
863 axiale de pieux forés dans des sols fins. *Bull Liaison Lab Ponts Chauss*, (119).

- 864 Garbellini, C., and Laloui, L. 2019a. Three-dimensional finite element analysis of piled rafts
865 with energy piles. *Computers and Geotechnics*, **114**(February): 103115. Elsevier.
866 doi:10.1016/j.compgeo.2019.103115.
- 867 Garbellini, C., and Laloui, L. 2019b. Thermal stress analysis of energy piles. *Géotechnique*,:
868 1–12. doi:10.1680/jgeot.19.p.208.
- 869 Gawecka, K.A., Tabora, D.M.G., Potts, D.M., Cui, W., Zdravković, L., and Haji Kasri, M.S.
870 2017. Numerical modelling of thermo-active piles in London Clay. *Proceedings of the*
871 *Institution of Civil Engineers-Geotechnical Engineering*, **170**(3): 201–219. Thomas
872 Telford Ltd.
- 873 Georgiadis, K., Skordas, D., Kamas, I., and Comodromos, E. 2020. Heating and cooling
874 induced stresses and displacements in heat exchanger piles in sand. *Renewable Energy*,
875 **147**: 2599–2617. Elsevier Ltd. doi:10.1016/j.renene.2018.11.078.
- 876 Guo, Y., Songyu, L., Guozhu, Z., and Lei, C. 2018. Investigation on the thermo-
877 mechanical behavior of free constrained full-scale PHC energy pile in multi-layer strata.
878 *Chinese Journal of Rock Mechanics and Engineering*, **38**.
- 879 Hu, B., and Luo, Z. 2020. Life-cycle probabilistic geotechnical model for energy piles.
880 *Renewable Energy*, **147**: 741–750. Elsevier Ltd. doi:10.1016/j.renene.2019.09.022.
- 881 Iodice, C., Di Laora, R., and Mandolini, A. 2020. Analytical Solutions for Ultimate Limit
882 State Design of Thermal Piles. *Journal of Geotechnical and Geoenvironmental*
883 *Engineering*, **146**(5): 1–14. doi:10.1061/(ASCE)GT.1943-5606.0002204.
- 884 Iodice, C., Di Laora, R., and Mandolini, A. 2023. A practical method to design thermally
885 stressed piles. *Géotechnique*, **73**(1): 30–43. doi:10.1680/jgeot.20.P.231.
- 886 Jeong, S., Lim, H., Lee, J.K., and Kim, J. 2014. Thermally induced mechanical response of
887 energy piles in axially loaded pile groups. *Applied Thermal Engineering*, **71**(1): 608–
888 615. Elsevier Ltd. doi:10.1016/j.applthermaleng.2014.07.007.
- 889 KALANTIDOU, A., TANG, A.M., PEREIRA, J.-M., and HASSEN, G. 2012. Preliminary
890 study on the mechanical behaviour of heat exchanger pile in physical model.
891 *Géotechnique*, **62**(11): 1047–1051. doi:10.1680/geot.11.T.013.
- 892 Kezdi, A. 1957. Bearing Capacity of Piles and Pile Groups. *In Proceedings of 4th*
893 *International Conference on Soil Mechanics and Foundation Engineering*. . . London.
894 pp. 46–51.
- 895 Knellwolf, C., Peron, H., and Laloui, L. 2011. Geotechnical Analysis of Heat Exchanger
896 Piles. *Journal of Geotechnical and Geoenvironmental Engineering*, **137**(10): 890–902.
897 doi:10.1061/(ASCE)GT.1943-5606.0000513.
- 898 Kong, G., Fang, J., Huang, X., Liu, H., and Abuel-Naga, H. 2020. Thermal induced horizontal
899 earth pressure changes of pipe energy piles under multiple heating cycles.
900 *Geomechanics for Energy and the Environment*, (xxxx): 100228. Elsevier Ltd.
901 doi:10.1016/j.gete.2020.100228.
- 902 Laloui, L., Nuth, M., and Vulliet, L. 2006. Experimental and numerical investigations of the
903 behaviour of a heat exchanger pile. *International Journal for Numerical and Analytical*
904 *Methods in Geomechanics*, **30**(8): 763–781. doi:10.1002/nag.499.
- 905 Lee, C.Y. 1993. Pile groups under negative skin friction. *Journal of geotechnical engineering*,

906 **119**(10): 1587–1600. American Society of Civil Engineers.

907 Lee, K.M., and Xiao, Z.R. 2001. A simplified nonlinear approach for pile group settlement
908 analysis in multilayered soils. *Canadian Geotechnical Journal*, **38**(5): 1063–1080. NRC
909 Research Press Ottawa, Canada. doi:http://cgj.nrc.ca.

910 Lin, Z.-Y., and Dai, Z.-H. 2014. Interaction coefficients method for calculating piles group
911 settlements considering reinforcing and restraining effect.

912 Liu, S., Zhang, Q., Cui, W., Liu, G., and Liu, J. 2022. A simple method for analyzing
913 thermomechanical response of an energy pile in a group. *Geomechanics for Energy and
914 the Environment*, (xxxx): 100309. Elsevier Ltd. doi:10.1016/j.gete.2022.100309.

915 Luo, Z., and Hu, B. 2019. Probabilistic design model for energy piles considering soil spatial
916 variability. *Computers and Geotechnics*, **108**(December 2018): 308–318. Elsevier.
917 doi:10.1016/j.compgeo.2019.01.003.

918 Mimouni, T., and Laloui, L. 2015. Behaviour of a group of energy piles. *Canadian
919 Geotechnical Journal*, **52**(12): 1913–1929. doi:10.1139/cgj-2014-0403.

920 Moradshahi, A., Faizal, M., Bouazza, A., and McCartney, J.S. 2020. Effect of nearby piles
921 and soil properties on the thermal behaviour of a field-scale energy pile. *Canadian
922 Geotechnical Journal*,: 1–41. doi:10.1139/cgj-2020-0353.

923 Murphy, K.D., McCartney, J.S., and Henry, K.S. 2015. Evaluation of thermo-mechanical and
924 thermal behavior of full-scale energy foundations. *Acta Geotechnica*, **10**(2): 179–195.
925 doi:10.1007/s11440-013-0298-4.

926 Mylonakis, G., and Gazetas, G. 1998. Settlement and additional internal forces of grouped
927 piles in layered soil. *Geotechnique*, **48**(1): 55–72. Thomas Telford Ltd.

928 Najma, A., and Sharma, J. 2021. Incremental load transfer analysis of an energy pile under
929 arbitrary mechanical and thermal loads. *Geomechanics for Energy and the Environment*,
930 **28**: 100243. Elsevier Ltd. doi:10.1016/j.gete.2021.100243.

931 Ng, C.W.W., Farivar, A., Gomaa, S.M.M.H., Shakeel, M., and Jafarzadeh, F. 2021.
932 Performance of elevated energy pile groups with different pile spacing in clay subjected
933 to cyclic non-symmetrical thermal loading. *Renewable Energy*, **172**: 998–1012.
934 doi:10.1016/j.renene.2021.03.108.

935 Ng, C.W.W., Gunawan, A., Shi, C., Ma, Q.J., and Liu, H.L. 2016. Centrifuge modelling of
936 displacement and replacement energy piles constructed in saturated sand: a comparative
937 study. *Géotechnique Letters*, **6**(1): 34–38. doi:10.1680/jgele.15.00119.

938 Ng, C.W.W., and Ma, Q.J. 2019. Energy pile group subjected to non-symmetrical cyclic
939 thermal loading in centrifuge. *Geotechnique Letters*, **9**(3): 173–177.
940 doi:10.1680/jgele.18.00161.

941 Ng, C.W.W., Shi, C., Gunawan, A., Laloui, L., and Liu, H.L. 2015. Centrifuge modelling of
942 heating effects on energy pile performance in saturated sand. *Canadian Geotechnical
943 Journal*, **52**(8): 1045–1057. doi:10.1139/cgj-2014-0301.

944 Nguyen, V.T., Wu, N., Gan, Y., Pereira, J.-M., and Tang, A.M. 2019. Long-term thermo-
945 mechanical behaviour of energy piles in clay. *Environmental Geotechnics*, (2015): 1–12.
946 doi:10.1680/jenge.17.00106.

947 Olgun, C.G., Ozudogru, T.Y., and Arson, C.F. 2014. Thermo-mechanical radial expansion of
948 heat exchanger piles and possible effects on contact pressures at pile–soil interface.
949 *Géotechnique Letters*, **4**(3): 170–178. doi:10.1680/geolett.14.00018.

950 Ozudogru, T.Y., Olgun, C.G., and Arson, C.F. 2015. Analysis of friction induced thermo-
951 mechanical stresses on a heat exchanger pile in isothermal soil. *Geotechnical and*
952 *Geological Engineering*, **33**: 357–371. Springer.

953 Pei, H., Song, H., Meng, F., and Liu, W. 2022a. Long-term thermomechanical displacement
954 prediction of energy piles using machine learning techniques. *Renewable Energy*, **195**:
955 620–636. Elsevier Ltd. doi:10.1016/j.renene.2022.06.057.

956 Pei, H., Song, H., Zhou, C., Yang, Q., and Xiao, D. 2022b. Cyclic t-z model for the long-term
957 thermomechanical analysis of energy piles. *Canadian Geotechnical Journal*,: 1–45.
958 doi:10.1139/cgj-2022-0011.

959 Rammal, D., Mroueh, H., and Burlon, S. 2018. Impact of thermal solicitations on the design
960 of energy piles. *Renewable and Sustainable Energy Reviews*, **92**(April): 111–120.
961 Elsevier Ltd. doi:10.1016/j.rser.2018.04.049.

962 Randolph, M.F. 1994. Design methods for pile groups and piled rafts. *In* International
963 conference on soil mechanics and foundation engineering. pp. 61–82.

964 Randolph, M.F., and Wroth, C.P. 1978. Analysis of Deformation of Vertically Loaded Piles.
965 *Journal of the Geotechnical Engineering Division*, **104**(12): 1465–1488. American
966 Society of Civil Engineers. doi:10.1061/AJGEB6.0000729.

967 Randolph, M.F., and Wroth, C.P. 1979. An analysis of the vertical deformation of pile groups.
968 *Geotechnique*, **29**(4): 423–439. Thomas Telford Ltd.

969 Ravera, E., Sutman, M., and Laloui, L. 2020a. Load Transfer Method for Energy Piles in a
970 Group with Pile-Soil-Slab-Pile Interaction. *Journal of Geotechnical and*
971 *Geoenvironmental Engineering*, **146**(6): 1–17. doi:10.1061/(ASCE)GT.1943-
972 5606.0002258.

973 Ravera, E., Sutman, M., and Laloui, L. 2020b. Analysis of the interaction factor method for
974 energy pile groups with slab. *Computers and Geotechnics*, **119**(February): 103294.
975 Elsevier. doi:10.1016/j.compgeo.2019.103294.

976 Rotta Loria, A.F., Catalá Oltra, J. V., and Laloui, L. 2020a. Equivalent pier analysis of full-
977 scale pile groups subjected to mechanical and thermal loads. *Computers and*
978 *Geotechnics*, **120**(July 2019): 103410. Elsevier. doi:10.1016/j.compgeo.2019.103410.

979 Rotta Loria, A.F., Catalá Oltra, J. V., and Laloui, L. 2020b. Equivalent pier analysis of full-
980 scale pile groups subjected to mechanical and thermal loads. *Computers and*
981 *Geotechnics*, **120**(July 2019): 103410. Elsevier. doi:10.1016/j.compgeo.2019.103410.

982 Rotta Loria, A.F., and Coulibaly, J.B. 2021. Thermally induced deformation of soils: A
983 critical overview of phenomena, challenges and opportunities. *Geomechanics for Energy*
984 *and the Environment*, **25**: 100193. Elsevier Ltd. doi:10.1016/j.gete.2020.100193.

985 Rotta Loria, A.F., and Laloui, L. 2016. The interaction factor method for energy pile groups.
986 *Computers and Geotechnics*, **80**: 121–137. The Authors.
987 doi:10.1016/j.compgeo.2016.07.002.

988 Rotta Loria, A.F., and Laloui, L. 2017a. The equivalent pier method for energy pile groups.
989 *Geotechnique*, **67**(8): 691–702. doi:10.1680/jgeot.16.P.139.

990 Rotta Loria, A.F., and Laloui, L. 2017b. Thermally induced group effects among energy piles.
991 *Geotechnique*, **67**(5): 374–393. doi:10.1680/jgeot.16.P.039.

992 Rotta Loria, A.F., and Laloui, L. 2018. Group action effects caused by various operating
993 energy piles. *Geotechnique*, **68**(9): 834–841. doi:10.1680/jgeot.17.P.213.

- 994 Rotta Loria, A.F., Vadrot, A., and Laloui, L. 2018. Analysis of the vertical displacement of
 995 energy pile groups. *Geomechanics for Energy and the Environment*, **16**: 1–14. Elsevier
 996 Ltd. doi:10.1016/j.gete.2018.04.001.
- 997 Saeidi Rashk Olia, A., Cossel, A.E., and Perić, D. 2022. Analytical Solutions for
 998 Thermomechanical Soil–Structure Interaction in Single Semifloating Energy Piles
 999 Embedded in a Layered Soil Profile. *Journal of Geotechnical and Geoenvironmental*
 1000 *Engineering*, **148**(10): 4022080. American Society of Civil Engineers.
- 1001 Saggu, R., and Chakraborty, T. 2015. Cyclic Thermo-Mechanical Analysis of Energy Piles in
 1002 Sand. *Geotechnical and Geological Engineering*, **33**(2): 321–342. doi:10.1007/s10706-
 1003 014-9798-8.
- 1004 Saggu, R., and Chakraborty, T. 2016. Thermomechanical Response of Geothermal Energy
 1005 Pile Groups in Sand. *International Journal of Geomechanics*, **16**(4): 04015100.
 1006 doi:10.1061/(ASCE)GM.1943-5622.0000567.
- 1007 Seed, H.B., and Reese, L.C. 1957. The action of soft clay along friction piles. *Transactions of*
 1008 *the American Society of Civil Engineers*, **122**(1): 731–754. American Society of Civil
 1009 Engineers.
- 1010 Selvadurai, A.P.S. 2013. *Elastic analysis of soil-foundation interaction*. Elsevier.
- 1011 Song, H., and Pei, H. 2022. A Nonlinear Softening Load-Transfer Approach for the
 1012 Thermomechanical Analysis of Energy Piles. *International Journal of Geomechanics*,
 1013 **22**(5): 1–14. doi:10.1061/(ASCE)GM.1943-5622.0002358.
- 1014 Song, H., Pei, H., Xu, D., and Cui, C. 2020. Performance study of energy piles in different
 1015 climatic conditions by using multi-sensor technologies. *Measurement*,: 107875.
 1016 doi:https://doi.org/10.1016/j.measurement.2020.107875.
- 1017 Song, H., Pei, H., Zhou, C., Zou, D., and Cui, C. 2022. Calculation of the representative
 1018 temperature change for the thermomechanical design of energy piles. *Geomechanics for*
 1019 *Energy and the Environment*, **29**(xxxx): 100264. Elsevier Ltd.
 1020 doi:10.1016/j.gete.2021.100264.
- 1021 Suryatriyastuti, M.E., Burlon, S., and Mroueh, H. 2016. On the understanding of cyclic
 1022 interaction mechanisms in an energy pile group. *International Journal for Numerical and*
 1023 *Analytical Methods in Geomechanics*, **40**(1): 3–24. doi:10.1002/nag.2382.
- 1024 Suryatriyastuti, M.E., Mroueh, H., and Burlon, S. 2012. Understanding the temperature-
 1025 induced mechanical behaviour of energy pile foundations. *Renewable and Sustainable*
 1026 *Energy Reviews*, **16**(5): 3344–3354. Elsevier Ltd. doi:10.1016/j.rser.2012.02.062.
- 1027 Suryatriyastuti, M.E., Mroueh, H., and Burlon, S. 2014. A load transfer approach for studying
 1028 the cyclic behavior of thermo-active piles. *Computers and Geotechnics*, **55**: 378–391.
 1029 Elsevier Ltd. doi:10.1016/j.compgeo.2013.09.021.
- 1030 Sutman, M., Brettmann, T., and Olgun, C.G. 2019a. Full-scale in-situ tests on energy piles:
 1031 Head and base-restraining effects on the structural behaviour of three energy piles.
 1032 *Geomechanics for Energy and the Environment*, **18**: 56–68. Elsevier Ltd.
 1033 doi:10.1016/j.gete.2018.08.002.
- 1034 Sutman, M., Olgun, C.G., and Laloui, L. 2019b. Cyclic Load–Transfer Approach for the
 1035 Analysis of Energy Piles. *Journal of Geotechnical and Geoenvironmental Engineering*,
 1036 **145**(1): 04018101. doi:10.1061/(ASCE)GT.1943-5606.0001992.
- 1037 Sutman, M., Speranza, G., Ferrari, A., Larrey-Lassalle, P., and Laloui, L. 2020. Long-term

1038 performance and life cycle assessment of energy piles in three different climatic
1039 conditions. *Renewable Energy*, **146**: 1177–1191. Elsevier Ltd.
1040 doi:10.1016/j.renene.2019.07.035.

1041 Trochanis, A.M., Bielak, J., and Christiano, P. 1991. Three-dimensional nonlinear study of
1042 piles. *Journal of Geotechnical Engineering*, **117**(3): 429–447. American Society of Civil
1043 Engineers.

1044 Wang, A.D., Wang, W.D., Huang, M.S., Wu, J.B., Sheil, B.B., and McCabe, B.A. 2016.
1045 Interaction factor for large pile groups. *Géotechnique Letters*, **6**(3): 234–240.
1046 doi:10.1680/jgele.16.00082.

1047 Wang, B., Bouazza, A., Singh, R.M., Haberfield, C., Barry-Macaulay, D., and Baycan, S.
1048 2015. Posttemperature Effects on Shaft Capacity of a Full-Scale Geothermal Energy
1049 Pile. *Journal of Geotechnical and Geoenvironmental Engineering*, **141**(4): 04014125.
1050 doi:10.1061/(ASCE)GT.1943-5606.0001266.

1051 Wong, K.S., and Teh, C.I. 1995. Negative skin friction on piles in layered soil deposits.
1052 *Journal of Geotechnical Engineering*, **121**(6): 457–465. doi:10.1061/(ASCE)0733-
1053 9410(1995)121:6(457).

1054 Wu, D., Liu, H., Kong, G., and Ng, C.W.W. 2020. Interactions of an Energy Pile with Several
1055 Traditional Piles in a Row. *Journal of Geotechnical and Geoenvironmental Engineering*,
1056 **146**(4): 1–9. doi:10.1061/(ASCE)GT.1943-5606.0002224.

1057 Wu, D., Liu, H., Kong, G., and Rotta Loria, A.F. 2021. Thermo-mechanical behavior of a
1058 full-scale energy pile equipped with a spiral pipe configuration. *Canadian Geotechnical*
1059 *Journal*,: cgj-2020-0162. doi:10.1139/cgj-2020-0162.

1060 Yavari, N., Tang, A.M., Pereira, J.-M., and Hassen, G. 2014. A simple method for numerical
1061 modelling of mechanical behaviour of an energy pile. *Géotechnique Letters*, **4**(2): 119–
1062 124. doi:10.1680/geolett.13.00053.

1063 Yavari, N., Tang, A.M., Pereira, J.M., and Hassen, G. 2016a. Mechanical behaviour of a
1064 small-scale energy pile in saturated clay. *Geotechnique*, **66**(11): 878–887.
1065 doi:10.1680/jgeot.15.T.026.

1066 Yavari, N., Tang, A.M., Pereira, J.M., and Hassen, G. 2016b. Effect of temperature on the
1067 shear strength of soils and the soil–structure interface. *Canadian Geotechnical Journal*,
1068 **53**(7): 1186–1194. doi:10.1139/cgj-2015-0355.

1069 Yazdani, S., Helwany, S., and Olgun, G. 2019a. Experimental evaluation of shear strength of
1070 kaolin clay under cyclic and noncyclic thermal loading. *Geotechnical Testing Journal*,
1071 **42**(6): 1518–1548. doi:10.1520/GTJ20180020.

1072 Yazdani, S., Helwany, S., and Olgun, G. 2019b. Investigation of Thermal Loading Effects on
1073 Shaft Resistance of Energy Pile Using Laboratory-Scale Model. *Journal of Geotechnical*
1074 *and Geoenvironmental Engineering*, **145**(9): 04019043. doi:10.1061/(ASCE)GT.1943-
1075 5606.0002088.

1076 Zhang, Q., Liu, S., Zhang, S., Zhang, J., and Wang, K. 2016. Simplified non-linear
1077 approaches for response of a single pile and pile groups considering progressive
1078 deformation of pile–soil system. *Soils and Foundations*, **56**(3): 473–484. Elsevier.
1079 doi:10.1016/j.sandf.2016.04.013.

1080 Zhou, H., Kong, G., Liu, H., Wu, Y., and Li, G. 2016. A novel cavity expansion-based
1081 analytical tool and its potential application for energy pile foundation. *In Proceedings of*

1082
1083

the 1st International Conference on Energy Geotechnics, ICEGT. pp. 359–365.