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# Long-term mechanical performance of geothermal diaphragm walls in stiff clay

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22 **ABSTRACT**

23 Diaphragm wall equipped with ground heat exchangers is one type of thermo-active  
24 foundations, which harness the energy stored by the ground for heating and/or cooling  
25 buildings. Past investigations on geothermal diaphragm walls mainly focused on the thermal  
26 performance, but paid little attention on their mechanical response to geothermal energy  
27 operation. This paper conducts thermo-hydro-mechanical (THM) finite element analyses to  
28 investigate the long-term performance of geothermal diaphragm walls in stiff clay. The  
29 numerical analyses take account of both the station excavation process in short-term and long-  
30 term behaviour of the diaphragm wall. The long-term soil-structure interaction simulation  
31 includes three scenarios, examining the effects of ground consolidation, external thermal  
32 solicitations and seasonal geothermal operation, respectively. A comparison between the  
33 mechanical behaviour of the geothermal diaphragm wall and that of the same wall without  
34 geothermal activation indicates that geothermal operation may have an impact on structural  
35 serviceability issues (e.g. thermal-induced concrete cracks) although unlikely cause critical  
36 safety problems. In particular, the ground settlement near the station is very sensitive to the  
37 stiffness degradation of the stiff clay during geothermal operation, while specific attention  
38 should be given to the structural performance at the connections between the wall and slabs  
39 due to thermo-induced additional stress concentration.

40

41 **KEYWORDS**

42 Geothermal foundation

43 Diaphragm wall

44 Long-term mechanical behaviour

45 Long-term ground settlement

46 Thermo-hydro-mechanical analysis

## 47 **1 Introduction**

48 Geothermal energy is a type of renewable energy generated and stored under the ground surface  
49 with the potential to reduce fossil energy consumption. It has attracted increasing attention  
50 from the engineering community all over the world. For most European countries, the seasonal  
51 ground temperatures remain relatively constant at a certain depth, e.g. 10-15°C down to a depth  
52 of approximately 50 m (Brandl, 2006, Adam and Markiewicz, 2009). The utilisation of this  
53 shallow geothermal energy allows heat exchange with the ground for cooling and heating civil  
54 infrastructures: in winter, heat is extracted from the ground to satisfy heating needs, whereas  
55 heat is injected into the ground during summer for cooling demands. Over the last few decades,  
56 the technologies for the exploitation of low enthalpy geothermal energy have been developed  
57 significantly, especially thermo-active underground structures.

58 Unlike conventional ground heat exchanger (GHE) systems, e.g. earth collectors or borehole  
59 heat exchangers, thermo-active ground structures are more cost-effective and environmentally  
60 friendly (Brandl, 2006). This technology embeds heat exchanger pipes into underground  
61 structural elements such as slabs, anchors, tunnel lining, pile foundations and diaphragm walls,  
62 enabling the structural system to absorb geothermal resources and sustain loads at the same  
63 time. The main benefits of thermo-active structures include: preventing groundwater pollution,  
64 saving drilling cost, boosting heat transfer efficiency, and reducing underground space  
65 occupation.

66 In the past, the majority of past investigations and practices of thermo-active structures focused  
67 on energy piles (Bourne-Webb et al., 2009, Brandl, 1998, Brandl, 2006, Gashti et al., 2014,  
68 Jeong et al., 2014, Knellwolf et al., 2011, Laloui et al., 2006, Ouyang, 2014, Suryatriyastuti et  
69 al., 2012). Recently, growing attention has been attracted to other thermo-active structures, for  
70 example, diaphragm walls (Amis et al., 2010, Coletto and Sterpi, 2016, Di Donna et al., 2017,  
71 Sterpi et al., 2017, Sun et al., 2013, Xia et al., 2012, Sterpi et al., 2014, Rammal et al., 2016,  
72 Barla et al., 2018). Diaphragm walls are widely adopted as earth retaining structures for deep  
73 pit foundations, such as metro stations or high-rise building foundations; given the same  
74 concrete volume, diaphragm wall may provide relatively larger heat-exchanging contact area  
75 with surrounding ground than piles, which in turn enhance the heat exchange efficiency  
76 (Brandl, 2006).

77 Despite the increasing research outcomes on the thermal performance study of geothermal  
78 diaphragm walls (Adam and Markiewicz, 2009, Brandl, 2006, Di Donna et al., 2017, Sun et  
79 al., 2013, Xia et al., 2012, Barla et al., 2018), the study on the mechanical aspect of energy  
80 walls is still scarce, even though some investigations have been made recently (Bourne-Webb  
81 et al., 2016, Coletto and Sterpi, 2016, Rui, 2014, Rui and Yin, 2018, Barla et al., 2018, Sterpi  
82 et al., 2017, Rammal, 2017, Dong et al., 2018). Mimouni and Laloui (2015) conducted a full-  
83 scale experimental site with four energy test piles, and indicated that differential displacements  
84 between conventional and energy piles could induce potential damage to the supported  
85 superstructure in stiff soil layers. Even though their results showed that the magnitudes of  
86 differential ground movements due to energy piles are significantly low, it's still essential to  
87 examine the undetermined mechanical performance due to energy diaphragm walls. The  
88 analysis of a geothermal diaphragm wall can be more complicated than an energy pile, in terms  
89 of the surrounding ground conditions. The pile foundation of a building is usually entirely  
90 embedded in soil, whereas some part of a diaphragm wall is exposed to the air. The heating  
91 and cooling operation causes the soil and the concrete to expand and shrink, respectively. As a  
92 result, the thermal-operation induced differential displacement between the soil side and the  
93 soil-free side of the wall may affect the performance of the diaphragm wall in the long run.

94 Bourne-Webb et al. (2016) pointed out that the mechanical response (displacement and bending  
95 moment) of the thermal wall from the geothermal operation is limited, on the basis of a 2D  
96 symmetrical thermo-hydro-mechanical numerical model. Rui (2014) programmed in-house 2D  
97 finite element codes to investigate both the short-term and long-term THM responses of energy  
98 walls for the first time, based on a well-documented thermal diaphragm wall project in London.  
99 Later, Rui and Yin (2018) concluded that the effect of the geothermal operation on the long-  
100 term wall movement magnitude was small considering seasonal variations. Meanwhile, Barla  
101 et al. (2018) also conducted 2D TH analyses to investigate the thermal-induced mechanical  
102 effects on the wall in terms of the computed horizontal displacement and bending moment  
103 along the wall using a FLAC model. Further to 2D numerical analysis, Coletto and Sterpi  
104 (2016) and Sterpi et al. (2017) conducted a 3D numerical TH model to predict the wall  
105 movement and internal forces (axial force and bending moment) and indicated that the  
106 computed results is within the acceptable range of geotechnical safety. Rammal (2017)  
107 investigated the impact of various thermal solicitations and different soil thermo-mechanical  
108 properties on the structural performance (e.g. internal structural forces) of geothermal

109 diaphragm walls in Paris metropolitan underground stations, and provided some  
110 recommendations for the industrial designers. In addition, Dong et al. (2018) found a thermal-  
111 induced increase of axial strain in the wall and earth pressure at the soil-wall interface through  
112 both experimental and numerical modelling approaches. Most of past studies, however, usually  
113 consider soil-structure THM interaction in an idealised simplistic scenario (e.g. one-layer  
114 homogenous soil), but seldom compare the computed retaining wall behaviour against reliable  
115 field measurements. Due to lack of comprehensive field data of energy walls, the proposed  
116 finite element models could hardly be well validated and therefore may have difficulty in  
117 accurately predicting the geothermal retaining wall behaviour in the long term.

118 This paper mainly focuses on the investigation of the long-term performance of geothermal  
119 diaphragm walls in relation to the mechanical behaviour of structural elements and ground  
120 response. In this study, a THM numerical model using HSS model is performed based on the  
121 construction and design records from London Dean Street Station reported by Rui (2014). The  
122 finite element analysis considered the whole life of London Dean Street Geothermal Station:  
123 from station construction in the short term to long-term geothermal operation. In particular, the  
124 thermal effects due to external thermal solicitations (e.g. air temperature seasonal variation,  
125 soil temperature and station temperature) and seasonal geothermal operation were examined  
126 by specific modelling scenarios, respectively.

## 127 **2 Project overview**

128 Di Donna et al. (2017) collected the existing records of constructed geothermal diaphragm  
129 walls from studies available from the UK, Austria and China. Although some past studies have  
130 provided details of the energy efficiency, the field data on the mechanical performance of  
131 energy wall projects are rather rare, especially for the long term. Up to date, to the authors'  
132 best knowledge, only Rui (2014) reported some comprehensive monitoring data of the  
133 horizontal geothermal wall movement at the construction stage in London Dean Street Station  
134 Project. The field measurements at the short-term construction stage were used to test Rui  
135 (2014)'s finite element model, followed by the prediction of long-term wall behaviour, whereas  
136 there remain some major limitations in his study: 1) numerical accuracy; 2) model validation;  
137 and 3) various mechanical aspects.

- 138 • Compared with sophisticated commercial finite element software, Rui (2014) wrote his  
139 own in-house thermo-hydro-mechanical codes for soil-structure THM interaction.

140 Since his code is not yet open-source, the predicted diaphragm wall behaviour in his  
141 study can hardly be reproduced by other researchers without using the codes. There  
142 remains an arguable uncertainty of his FE code with regard to the accuracy and  
143 numerical stability if it has not yet been comprehensively examined by some  
144 international peers and / or independent third party.

- 145 • In order to match the field measurements, Rui (2014) purposely zeroed the computed  
146 wall displacements at the toe but failed to explain the reason in details. There is lack of  
147 justification, to the authors' best knowledge, for such intentional modification on the  
148 basis of past diaphragm wall studies.
- 149 • In terms of THM soil-structure interaction in the long term, Rui (2014) only focused on  
150 diaphragm wall behaviour and temperature-variation-induced soil volume change, but  
151 paid little attention on adjacent ground settlement and structural behaviour of the train  
152 station and other important mechanical behaviour, which may be sensitive to  
153 geothermal operation.

154 Considering the aforementioned limitations, this study conducted thermo-hydro-mechanical  
155 (THM) analysis to evaluate whole-life behaviour of geothermal station using sophisticated  
156 PLAXIS finite element software. The computed results of short-term wall displacements due  
157 to station construction are compared against the field measurements, followed by specific  
158 investigation of both geothermal diaphragm wall performance and ground response in the long  
159 term. The overview of this project is described as follows:

160 In London, there has been some energy foundations adopted in new or redeveloped station  
161 boxes. Dean Street Station is one of these geothermal boxes, known as the second thermal wall  
162 project in the UK, with 500 kW geothermal capacity. The station is located at the intersection  
163 of Dean Street and Oxford Street (red block C & D in Figure 1), consisting of two main boxes  
164 with different base levels. A combination of thermal piles and thermal walls has been installed  
165 in the station.

166 The station box was constructed using bottom-up method. Prior to the pit foundation  
167 excavation, a 1-meter-thick diaphragm wall trench (up to 41m depth) was constructed around  
168 the excavation site. 40-m-long absorber pipes were attached to the reinforcement cage and  
169 lowered into the trench (0.25 m from the soil-side surface of the wall), and later grouted  
170 together with the steel cage to form geothermal diaphragm wall panels. The foundation pit was

171 designed to be 28.9 m in depth and excavated following 5 stages as shown in Figure 2. Three  
172 temporary props and one slab were constructed to support the excavation for each stage. Due  
173 to access constraints at the site, the lowest prop was omitted during excavation as to save  
174 construction time and cost. After excavated to the designated elevation, slabs were cast from  
175 the base of the station, and the temporary props were replaced by slabs to form a five-level  
176 station box.

### 177 **3 Finite element model**

#### 178 **3.1 Model geometry**

179 For simplicity, a 2D plane strain THM analysis of London Dean Street Station is conducted  
180 using finite element software PLAXIS 2D (Brinkgreve et al., 2018), as shown in Figure 3. In  
181 PLAXIS, a fully coupled flow-deformation (i.e. soil-fluid coupled) and thermal transient  
182 calculations is adopted for long-term geothermal soil-structure interaction. The diaphragm wall  
183 around the station is set to be wished in place and the initial stress state (i.e. geostatic phase)  
184 for the short-term simulation is generated by the K0 procedure available in PLAXIS, while the  
185 initial stress balance for the long-term model is set automatically after the final phase of the  
186 short-term model. The excavation block is 32 m wide and 28.9 m deep, surrounded by 1-m-  
187 thick and 41-m-deep diaphragm wall panels. The diaphragm wall is mostly embedded in low-  
188 permeability clay including 23-m-thick London Clay and 9-m-thick Lambeth Group Clay. The  
189 model boundary is 160 m deep and extended 144 m laterally from excavation edges to both  
190 sides. The structural members used during construction are shown in refined mesh block of  
191 Figure 3: three temporary props (green in the figure, 1 m thickness), five slabs (grey in the  
192 figure, 1 m thickness) and a base slab (2 m thickness).

193 The model consists of 10011 15-node triangular elements. For better accuracy, the finite  
194 element meshes around the excavation pit are refined, whereas coarser meshes are adopted  
195 away from the station as to save computational cost. Besides, the geothermal operation mode  
196 in this paper is considered as symmetrical operation mode (the geothermal systems at both  
197 sides of the diaphragm wall are activated), whereas the model in this study is conducted as a  
198 full-scale model instead of a symmetric half-scale one, on the purpose of facilitating future  
199 study on asymmetric geothermal operation mode.



### 200 3.2 Boundary conditions

201 The water level is set to be 3 m below ground surface, while the pore pressure distribution is  
202 assumed to be hydrostatic prior to soil excavation. During station construction, the clayey soil  
203 layers (e.g. London clay and Lambeth Group) are assumed in undrained condition, whereas  
204 drainage is allowed at all model boundaries for long-term thermo-hydro-mechanical coupled  
205 analysis after construction. The hydraulic boundary conditions inside the station are set to be  
206 impermeable throughout soil excavation and long-term consolidation. The maximum negative  
207 pore pressure is controlled within -100 kPa to avoid suction cavitation; negative pore pressure  
208 lower than -100 kPa will result in perfect vacuum condition with zero absolute pressure in the  
209 soil, which is prohibitively unlikely to happen.

210 At the side and bottom boundaries of the model, the horizontal and vertical displacements are  
211 fixed. The dimension of this FE model is 10 times greater than the excavation site (see Figure  
212 3) as to minimise the boundary effect on the numerical results. The top boundary is free to  
213 move, allowing possible ground settlements to be induced by excavation, consolidation and  
214 temperature variations.

215 For simplicity, no adiabatic boundaries have been imposed at the contact with the external air  
216 inside the station. The heat transfer among the whole model is controlled by the thermal  
217 properties of the material, e.g. thermal conductivity. The configuration of thermal boundaries  
218 is illustrated in Figure 3. All side boundaries except the top boundary set to be an initial  
219 temperature, 12°C, same as the soil temperature, corresponding to the soil constant temperature  
220 at a depth 10-12m in Europe (Brandl, 2006), whilst the temperature of the top thermal boundary  
221 is varying with seasons. The temperature inside the station is kept constant at 18°C all year  
222 round, all the thermal boundaries inside the station and along the slabs set as 18°C when  
223 activated at the start. In this figure, the heat exchanger pipes inside the diaphragm are modelled  
224 as a plane element together with two thermal boundaries, which is able to generally consider  
225 the equivalent effect of 3D spaced heat exchange tubes by thermal function in the PLAXIS 2D  
226 model. The top thermal boundary and these two heat-exchanging boundaries are controlled by  
227 thermal functions inside PLAXIS. In Fully coupled flow-deformation analysis, the temperature  
228 set for each boundary or material block is only used to initialize the temperature at the  
229 beginning of the long-term simulation, while the temperature afterwards change time-  
230 dependently (Brinkgreve et al., 2018).

### 231 3.3 Material properties

#### 232 3.3.1 Structural properties

233 The temporary props for construction stages are made of 1-m-diameter hollow steel tubes,  
234 modelled as node-to-node anchors, while slabs and diaphragm walls are modelled as concrete  
235 polygon entities in PLAXIS. Compared to plate elements, the use of the concrete clusters for  
236 walls and slabs enables to simulate the temperature variations inside the geothermal diaphragm  
237 wall and slabs more realistically. The material properties of anchors and concrete are listed in  
238 Table 1 and Table 2, respectively. For simplicity, the solid thermal expansion mode is set to be  
239 linear.

240 Due to creep and relaxation over time, Young's modulus of diaphragm wall is assumed to be  
241 26GPa (70% of the original 37GPa for the C50/60 concrete) for the short-term construction  
242 stage, while 19GPa (50% of the original value) was adopted for the long-term analysis as  
243 advised in CIRIA C580 by Gaba et al. (2003). For simplicity, the stiffness of slabs at both  
244 construction and long-term stages remains constant at 26GPa.

#### 245 3.3.2 Soil properties

246 In terms of soil properties on site, Rui and Yin (2018) indicated that the use of non-linear elastic  
247 model for clayey layers (i.e. London Clay and Lambeth Group) in their FE model can predict  
248 short-term wall displacement in better agreement with the field measurements than that by  
249 linear elastic model. Similar findings are also noted in this study. To simulate soil-structure  
250 interaction realistically without compromising computational cost, this FE analysis adopted  
251 Hardening soil model with small-strain stiffness (HSS) model for the nonlinear elastoplastic  
252 behaviour of clayey soil and Mohr-Coulomb (MC) model for nonclayey soils near the ground  
253 surface. The mechanical and thermal properties for soil layers are listed in Table 3 and Table  
254 4, respectively. Linear thermal expansion coefficients are assumed for all soil materials in the  
255 numerical simulation. In addition, the specific material properties of HSS models are listed in  
256 Table 5.

257 Most soil properties listed in Table 2, Table 3 and Table 4 were based on Crossrail design  
258 guideline (Rui, 2014). For better accuracy, the parameter  $c$  and  $\phi$  for Lambeth Group were  
259 determined according to the upper bound data suggested by Hight et al. (2004). The parameters  
260 of HSS model were also calibrated against the experimental lab tests available in literature:  
261 both London Clay A3 and A2 were determined by matching the shear modulus with triaxial

262 test data from Gasparre (2005); the HSS model parameters of both Lambeth Group UMC and  
263 LMC were calibrated by matching the shear modulus with the undrained young's modulus  
264 from Hight et al. (2004).

### 265 **3.4 Geothermal scenarios**

#### 266 **3.4.1 Construction phase and long-term phases**

267 This study aims to evaluate the influence of geothermal operation on the mechanical  
268 performance of structural elements and surrounding ground response. In general, the  
269 mechanical behaviour of geothermal diaphragm wall system is mainly governed by three  
270 factors: consolidation, external thermal solicitations (e.g. air temperature seasonal variation,  
271 soil temperature and station temperature) and geothermal operation. In order to separate these  
272 aspects and analyse the influence one after another, this study considered four modelling  
273 scenarios: one identical short-term scenario followed by three different long-term scenarios.

274 1A) Construction phase (HM): model validation stage, modelling the construction  
275 procedure and comparing the computed wall movement against the field motoring data;

276 2-A) Long-term phase A (HM): thermo-inactive scenario, evaluating the mechanical  
277 performance of geothermal diaphragm walls during long-term operation without any  
278 thermal solicitation, while only consolidation effect is activated;

279 2-B) Long-term phase B (THM): thermo-active scenario with no geothermal operation,  
280 evaluating the effect of seasonal temperature change on the mechanical behaviour of the  
281 structure, while both consolidation and external thermal solicitations are activated;

282 2-C) Long-term phase C (THM): thermo-active scenario with the geothermal operation,  
283 evaluating the effect of geothermal operation on the mechanical behaviour of the structure,  
284 while all three factors are activated.

#### 285 **3.4.2 Thermal boundaries**

286 There is no thermal boundary activated during the short-term phase, as temperature change  
287 (e.g. hydration heat of cement during concrete construction stage) generally has a much lower  
288 impact on the short-term mechanical behaviour of the diaphragm walls than that induced by  
289 soil excavation. While the thermal boundary conditions of the three aforementioned long-term  
290 phases are various in terms of external thermal solicitations and geothermal operation as shown  
291 in Figure 4. In long-term A phase, all the thermal boundaries in the model are set to deactivate  
292 temperature with no consideration of thermal effects (see Figure 4(a)). In long-term B phase,

293 all external thermal solicitations are activated, e.g. soil temperature, seasonal air temperature  
294 and station temperature. The thermal boundaries of the station box and the far-field soil in this  
295 study are set to be constant at 18°C and 12°C, respectively, assuming the temperature inside  
296 the station to be relatively invariant by the operation of ventilation system. The thermal  
297 boundary at the ground surface remains the same as the external air temperature subject to  
298 seasonal changes in London as shown in Figure 4(b). Long-term C phase is very similar to  
299 Long-term B phase, as shown in Figure 4(c) except that the temperature of heat exchange pipes  
300 inside the wall is activated, allowing the geothermal operation to affect the mechanical  
301 behaviour of the diaphragm wall.

302 Figure 5 shows the annual temperature range of London according to the local seasonal  
303 temperature variation (NOAA, 2018). The orange line in the graph represents the high level of  
304 temperature in London while the green line stands for the low level of temperature. For  
305 simplicity, this study adopts a step-fluctuating thermal function (Figure 5, dash line) to  
306 represent seasonal variations, cycling from 4°C for 6 months (winter cycle) to 23°C for 6  
307 months (summer cycle), for both air temperature boundaries and heat exchange fluid inside the  
308 wall. The selection of maximum temperature variation range and the presumed step-shaped  
309 thermal function considers the mechanical behaviour of geothermal foundation in a potentially  
310 most critical scenario on a conservative side (Rammal et al., 2018), whereas the determination  
311 of temperature range and thermal function may vary for various projects across the world on a  
312 case-by-case basis, depending on the designer's engineering judgement. The heat exchange  
313 fluid inside the diaphragm wall is assumed to be constant all the way from the inlet entrance to  
314 the outlet exit, since the thermal efficiency is not the primary concern of this study.

#### 315 **4 Geothermal diaphragm wall behaviour**

316 In this section, the computed short-term horizontal wall movement is compared against the  
317 field data to validate the FE model. Later, this FE model simulates thermo-hydro-mechanical  
318 (THM) soil-structure interaction to investigate long-term mechanical performance of the  
319 geothermal diaphragm wall system in five aspects: horizontal wall movement, vertical wall  
320 movement, ground settlement, basement heave and internal structural forces (normal force,  
321 shear force and bending moment). In all the output data, the sign convention are set as follows:  
322 1) for soil pressures (including total stress, effective stress and pore water pressure),  
323 compressive stress is represented by positive / plus sign and tensile stress is negative; 2) for

324 structural forces (N, Q and M), they are set to follow the general definitions of the structural  
325 mechanics. Normal force N presents as positive if in tension and negative for compression.  
326 While the shear force Q and bending moment M are positive if the material element is rotated  
327 in the counterclockwise direction, and negative for rotation in the clockwise direction.

#### 328 **4.1 Short-term diaphragm wall displacement**

329 In London Dean Street Station project, the excavation-induced wall displacement was recorded  
330 by inclinometers, where its bottom was assumed to be fixed with zero displacement. Figure 6  
331 compares the computed horizontal wall movements against the field measurements at four  
332 construction stages: the installations of Prop 2, Prop 3, Slab 2 and base slab. In general, the  
333 computed wall deflection shape matches with the field monitoring curves, whereas the  
334 maximum difference between them appears at the bottom of the wall at the last excavation  
335 stage (see Figure 6(d)).

336 Rui (2014) pointed out the wall movement at the bottom of the wall could hardly be measured  
337 by the inclinometers and therefore suggested to zero the computed displacements at the base  
338 of the wall. Nevertheless, the difference of the wall movement near the bottom of the wall  
339 between monitoring data and computed results is an universal problem observed by many  
340 researchers across the world (Cabarkapa et al., 2003, Hsieh et al., 2016, Lim et al., 2018, Nisha  
341 and Muttharam, 2017, Ou and Hsieh, 2011). Schwamb (2014) indicated the drawbacks of  
342 inclinometer measurement led to the underestimate of the movement at the bottom of the wall.  
343 The inclinometer can only obtain a relative deflection but not the absolute movement of the  
344 wall, as the displacement at the based point of the inclinometer can hardly be determined. There  
345 is a lack of justification to zero the wall movement at the toe.

346 Despite of the discrepancy between the computed results and field measurements, the FE model  
347 can generally simulate the short-term wall behaviour during excavation. Besides, the Customer  
348 Experience Executive of Transport for London Customer Services pointed out that the long-  
349 term field data was unable to be recorded in this case and difficult to collect over decades in  
350 practice. Therefore, this study predicts the thermal effect on the mechanical behaviour of  
351 geothermal diaphragm walls in the long term based on a short-term validated model rather than  
352 a long-term validated model.

## 353 4.2 Long-term train station behaviour

### 354 4.2.1 Long-term horizontal wall movement

355 Figure 7(a) shows the incremental horizontal displacement of the diaphragm wall after  
356 construction in the long term. The maximum incremental horizontal wall deformation of 6.8  
357 mm towards the excavation side after 30 years is obtained below the base slab, which is as  
358 much as 31% of the maximum horizontal movement of 21.9 mm due to construction. Since  
359 substantial soil was excavated between Slab 2 and Base Slab within a short period of time (11.2  
360 m depth of soil removed within 36 days), significant excess pore pressure was generated below  
361 the base slab after excavation. As soil consolidates with time, the ground below the base slab  
362 heaves up and in turn allows the adjoining D-wall to move towards the excavation side in the  
363 long term.

364 One significant movement (3.2 mm) towards the excavation side occurs at the depth of 21.4 m  
365 between Slab 2 and Slab 1, where a large amount of soil was excavated during construction as  
366 mentioned before. In addition, there are two notable horizontal movements towards the soil  
367 side, appearing between Slab 1 and Base Slab, and the bottom of the wall, 4.3 mm and 1.6 mm  
368 respectively. The lateral wall movement mode is very likely due to the combined effect of  
369 lateral soil pressure, excess pore water pressure dissipation and propping forces of the slabs.

370 Figure 7(b) shows the incremental horizontal movement of the wall under external thermal  
371 solicitations, which is generally consistent with the incremental wall deformation in Long-term  
372 A. The wall section above Base Slab shifts 1.2 mm towards the soil side immediately after  
373 construction, mainly due to the thermal expansion of the concrete slabs inside the station. When  
374 the thermal boundaries along the slabs (18°C) are activated in Long-term B, the 32-m-long  
375 slabs expand immediately, and pushes the part of the wall close to the station towards the soil  
376 side. There is negligible difference in wall displacement after 30 years between Long-term A  
377 and Long-term B below Base Slab. In general, the influence of external thermal solicitations  
378 on the incremental lateral movement of the wall is insignificant.

379 Figure 7(c) shows the incremental wall deformation during geothermal operation. Unlike the  
380 wall deflection behaviour in the first two scenarios, the part of wall movement above Slab 1 in  
381 Long-term C is significantly affected by the geothermal operation. The differential movement  
382 between Long-term B and Long-term C above Slab 1 starts to occur in the summer of the first  
383 operation year (1Y summer in the graph), where the wall section near the ground surface in

384 Long-term C moves 1.2 mm towards the excavation side in the opposite direction from with  
385 that in Long-term B. As mentioned earlier, the stiffness of soil layers at large shear strain level  
386 (over 0.0001) in HSS model is relatively small, hence, the wall deformation is sensitive to the  
387 mechanical change induced by the geothermal operation; that is, the soil stiffness degradation  
388 at particular site may notably affect the ground movements during geothermal operation.  
389 Nonetheless, the changes of wall deformation below Slab 1 are generally consistent with Long-  
390 term B, where the soil stiffness remains high at small strain level and as such little additional  
391 displacement is induced by the geothermal operation.

392 Furthermore, the wall movement also changes with seasonal operations. Above slab 5, the wall  
393 moves significantly towards the soil side in winters, approximately 0.8 mm greater than that in  
394 summers, while it gradually bends towards the excavation side between Slab 5 and Slab 4.

395

396 Figure 8 illustrates the mechanism for the temperature variation inside slabs and wall. In this  
397 particular thermal operation mode, there is little temperature variation for slabs, whereas a 14°C  
398 temperature variation develops along the wall thickness in winter (4°C near the soil side and  
399 18°C near the station side). In winters, the soil side of the wall (4°C) shrinks, whereas the  
400 station side (18°C) expands as shown in

401

402 Figure 8. Consequently, the temperature change across the wall thickness causes differential  
403 thermal displacement and greater wall bending deflection towards the soil side than that in  
404 Long-term B. In summers, since the absorber fluid temperature (23°C) is closer to the station  
405 temperature (18°C), the temperature difference along the wall thickness is small and therefore  
406 the wall deflection is almost the same as the results from Long-term B. Below slab 5, the D-  
407 wall displacement is similar to that in Long-term B. As soil pressure increases along the depth  
408 of the wall, the geothermal operation becomes less influential on the changes in wall  
409 movements.

410 In summary, in Long-term A, the horizontal wall movement is mainly controlled by the hydro-  
411 mechanical effects (e.g. lateral soil pressure and excess pore water pressure). When the external  
412 thermal solicitation is activated in Long-term B without geothermal operation, the thermal  
413 expansion of the slabs pushes part of the diaphragm wall towards the soil side. During the

414 geothermal operation in Long-term C, the geothermal operation has a great effect on the wall  
415 behaviour near the ground surface but becomes less influential with increasing soil depth.

#### 416 **4.2.2 Long-term vertical wall movement**

417 In addition, the vertical deflection of the diaphragm wall during geothermal operation is  
418 evaluated in relation to the risk of differential movement to the surface building.

419 Figure 9(a) shows the change of vertical wall movement in Long-term A without thermal  
420 solicitation. During ground consolidation after construction, the entire wall heaves over the  
421 next 30 years up to 7.2 mm near the ground surface level. When the external thermal  
422 solicitations is activated in Long-term B, the entire wall heaves up 2.9 mm greater than that in  
423 Long-term A due to the thermal extension of the concrete as shown in Figure 9(b). In contrast,  
424 the geothermal operation in Long-term C results in cyclical wall vertical displacement as shown  
425 in Figure 9(c). The wall heaves up during summers but shrinks in winters: the differential  
426 vertical displacement within a single year can be as much as 7.8 mm over 30 years after  
427 construction. Compared to wall displacement in Long-term B, the geothermal operation in  
428 Long-term C greatly affects the wall vertical displacement; for example, the maximum wall  
429 displacement in Long-term C after 30 years can build up to 18.1 mm, 8mm greater than that in  
430 Long-term B. In practice, if the geothermal diaphragm walls around an excavation are not  
431 operated in the same mode, the differential vertical movement induced by geothermal operation  
432 may potentially cause serviceability problems (e.g. cracks), particularly at the structural  
433 connections, for example, between the wall and the slabs.

#### 434 **4.2.3 Long-term ground settlement**

435 Geothermal operation will inevitably alter surrounding ground response and may in turn cause  
436 differential ground settlement, posing a risk to existing buildings nearby. According to the  
437 assessment method proposed by Burland and Wroth (1975), the assessment ratio of the relative  
438 settlement to the horizontal distance ( $\Delta/L$ ) will be particularly evaluated in the following  
439 discussion.

440 Wongsaroj (2005) suggested to analyse the ground settlement at a certain depth (e.g. 5 m)  
441 below the surface as to avoid the intervention from the temperature and seasonal changes in  
442 the air. Hence, this paper predicted the settlements at 5 m below the ground surface aiming to  
443 avoid any potential interference from the near-surface temperature change. During



444 consolidation, temperature change may have an influence on the coupled thermo-hydro-  
445 mechanical behaviour of soil. Over large temperature variation between 0°C and 180°C,  
446 heating at a high temperature can increase soil stiffness and strength (Houston et al., 1985),  
447 whereas the thermal effect on soil deformability and shear strength is not appreciable if  
448 temperature variation becomes smaller within 60°C (Miliziano, 1992, Lingnau et al., 1995). In  
449 this study, the range of temperature variation is as small as within 20°C during geothermal  
450 operation, and as such the coupling of temperature and consolidation is considered to be  
451 negligible.

452 Figure 10(a) shows the incremental ground settlement after construction during ground  
453 consolidation. The incremental ground movement distribution is generally in line with the long-  
454 term ground settlement for clayey soil deposit predicted by Ou and Lai (1994); the ground  
455 heaves progressively with time as the excess pore water pressure dissipates during  
456 consolidation. The maximum incremental ground settlement builds up to 8.3 mm after 30 years  
457 since excavation at a distance of 12.2 m from the edge of the wall; as much as 0.6 times of the  
458 excavation-induced ground settlement (14.0 mm) at the same position. The maximum  
459 assessment ratio in Long-term A achieved after 10 years geothermal operation is 0.018% as  
460 calculated in the graph.

461 Figure 10(b) shows the changes in the long-term ground settlement under external thermal  
462 solicitations. In the first winter after construction, the incremental ground settlement adjacent  
463 to the wall rises to 3.3 mm (1Y winter in Long-term B) greater than 1.0 mm for 1Y winter in  
464 Long-term A. After 30 years since construction, the peak incremental long-term ground  
465 settlement in Long-term B can build up to 10.0 mm at a distance 7.6 m from the edge of the  
466 wall, which is 1.7 mm higher than that in Long-term A. Conversely, the maximum assessment  
467 ratio is not much affected by the thermal solicitations, which is 0.011% obtained at 10Y (similar  
468 for winter and summer) and slightly smaller than it in Long-term A.

469 Figure 10(c) presents the incremental ground settlement during geothermal operation. The peak  
470 ground settlement after 30 years in Long-term C is 9.0 mm at a distance 15.1 m from the edge  
471 of the wall, which is similar as it in Long-term B. However, the assessment ratio in Long-term  
472 C is distinctly different from the other two modelling scenarios. In this graph, the maximum  
473 ratio at 30Y winter goes up to 0.073%, which is almost 5 times greater than that in the other  
474 situations in Long-term A & B. In particular, significant ground settlement builds up near the

475 edge of the wall due to the development of horizontal wall movement at the wall top section as  
476 discussed earlier. The seasonal geothermal operation has a notable effect on the ground  
477 movements near the diaphragm wall and the neighbouring buildings, although the assessment  
478 ratio generated by geothermal operation is still within the allowable deflection ratio (lower than  
479 0.2%) according to Burland and Wroth (1975).

#### 480 **4.2.4 Long-term basement heave**

481 In an underground structure, connections between the wall and slabs are supposed to distribute  
482 the vertical loads acting on the slabs (Gaba et al., 2003). Of particular interest is the base slab,  
483 which directly withstands the ground water and heave earth pressure underneath. Chan and  
484 Madabhushi (2017) pointed out that it is essential to design the substructure to withstand the  
485 pressure or accommodated heaving deflections before anticipated critical conditions occur in  
486 the long term. The long-term development of base slab heave is widely observed in deep  
487 basement embedded in clayey soil. For example, Chan et al. (2018) conducted geotechnical  
488 centrifuge testing on heave and pressure beneath base slab in excavation in over-consolidated  
489 clays, based on an 11-m-deep excavation project in London, which contains a total of 21 years  
490 of well-recorded heave monitoring data after construction. They noted that the development of  
491 heave with time was generally consistent with one-dimensional consolidation theory and  
492 estimated that long-term heave at the centre of the slab would reach 110 mm after excess pore  
493 water pressure dissipation for approximately 21 years. After that, the pore water pressure below  
494 the bottom basement will increase back to its hydrostatic value and together with a net change  
495 of 184kPa in total stress. In this study, the computed FE results of basement base case show  
496 similar deflection and stress development mechanism in consistent with the observed  
497 behaviour reported by Chan et al. (2018).

498 Figure 11 shows the development of long-term ground heave underneath the centre of the base  
499 slab (30.9 m below the ground surface) with square-root of time. Likewise, almost 80%  
500 consolidation has completed 30 years after the construction. Different from other behaviour  
501 aspects, the development of bottom centre movement and stresses of the base slab has included  
502 more phases, e.g. 40 years, 50 years, 60 years, 70 years and 80 years, in order to have a better  
503 present of the heaving mechanism. The rate and magnitude of heave displacement with time  
504 generally follows one-dimensional consolidation theory. Figure 12 shows the evolution of the  
505 stresses with time including total stress, pore water pressure and effective stress respectively  
506 under the centre of the base slab. After construction the effective stress reduces to zero very

507 quickly within 14 days, while the total stress and pore water pressure changes gradually with  
508 the dissipation of excess pore water pressure. The total stress is increased by 46 kPa due to the  
509 self-weight of the installed base slab, while the pore water pressure immediately after  
510 construction (i.e. the start of long-term consolidation) is -100 kPa owing to suction cavitation  
511 effect. The long-term heave of basement is mainly due to the dissipation of excess pore water  
512 pressure, and developments of heave and stresses are very similar among the three long-term  
513 scenarios A & B & C.

514 Figure 13(a) shows the changes of vertical base slab movement in Long-term A. The base slab  
515 gradually heaves up with the dissipation of excess pore water pressure, up to a maximum value  
516 of 74.8 mm at the foundation centreline after 30 years. After the base slab installation, there  
517 generates massive excess pore water pressure below the base slab. In the long term, the pore  
518 water pressure below the base slab recovers progressively with the dissipation of excess pore  
519 water pressure, contributing significantly to the uplift of the base slab. Compared with the  
520 centre of base slab, the vertical movement of the base slab at the corners is much smaller due  
521 to the constraints by the wall, which is only 8.7 mm after 30 years.

522 If the external thermal solicitation is activated (Long-term B), Figure 13(b) shows that the  
523 computed vertical base slab movement is consistent with Long-term A, except that the  
524 maximum displacements at the centre and the corners slightly increase by 4.2 mm and 1.0 mm  
525 respectively after 30 years. Figure 13(c) presents the base slab movement during the  
526 geothermal operation, which relatively shrinks during winters whereas expands in summers.  
527 The maximum movement at the centre and the corners after 30 years are 84.2 mm and 17.1  
528 mm, respectively, 6% and 58% greater than that in Long-term B. That is, geothermal operation  
529 may cause additional slab movements and therefore more serviceability issues (e.g. cracks)  
530 particularly at sensitive joint sections between the wall and the slabs.

#### 531 **4.2.5 Internal structural forces**

532 Another concern of geothermal foundation is the thermal effect on the internal structural forces,  
533 including normal force (N), shear force (Q) and bending moment (M). Figure 14 & Figure 15  
534 shows the internal structural forces inside the wall in Long-term A and Long-term B,  
535 respectively, where the green lines represent the total internal forces due to short-term  
536 excavation. Compared to the short-term internal forces, the incremental long-term internal  
537 forces above Base Slab are negligible for both Long-term A and Long-term B.

538 In contrast, Figure 16 shows that the internal forces above Base Slab oscillate with the seasonal  
539 geothermal operation for Long-term C, and the maximum long-term differential value builds  
540 up greater than the short-term excavation-induced forces. Nevertheless, considering the large  
541 the wall bending stiffness of ( $10^6$  kN•m<sup>2</sup>/m) and the oscillating internal forces ( $10^3$  kN/m for  
542 N,  $10^2$  kN/m for Q and  $10^2$  kN•m/m for M), the geothermal-operation-induced oscillation  
543 effect is small and negligible.

544 Some notable stress concentrations appear at the levels of slabs, due to the relative movement  
545 between the wall and the slab. The stress concentration mainly depends on the diaphragm wall  
546 deflection which varies along the depth. The most critical stress concentration occurs at the  
547 connections between the wall and the deepest base slab, whilst the other slabs, e.g. Slab 1 or  
548 Slab 2, develop similar stress concentration as the base slab but in smaller magnitude.

549 For simplicity, only the computed results of the internal structural forces inside the base slab  
550 are shown in Figure 17, Figure 18, and Figure 19 for Long-term A & B & C, respectively.  
551 Compared with the short-term excavation-induced forces, internal structural forces inside the  
552 base slab changes significant during the long term (green curves), mainly caused by the  
553 dissipation of excess pore water pressure underneath the base slab. The comparison of Long-  
554 term B & C (Figure 18 & Figure 19) against Long-term A (Figure 17) indicates that the external  
555 thermal solicitations and seasonal geothermal operation do not have significant effect on the  
556 shear forces and bending moment, whereas some oscillations develop at normal forces due to  
557 the thermal solicitation from the station.

558 In general, the effect of thermal solicitations on the internal structural forces are negligible for  
559 both the wall and the slabs, except for some notable oscillations of normal forces in Long-term  
560 C. In particular, the maximum internal forces occur around the base slab, which can be  
561 considered as the most critical section for the design of geothermal deep foundation.

## 562 **5 Conclusion**

563 Geothermal diaphragm walls may act both as a renewable and clean energy source as well as  
564 load-bearing structural elements. Compared to geothermal piles, the mechanical behaviour of  
565 geothermal diaphragm walls has not yet been well-understood. This study conducted a thermo-  
566 hydro-mechanical finite element analysis to evaluate the effect of thermal solicitation due to  
567 geothermal operation on the long-term mechanical performance of diaphragm walls, with

568 regard to both structural behaviour (wall movement, basement heave and internal structural  
569 forces) and geotechnical response (ground settlement). The main conclusions of this paper are  
570 listed as follows:

571 1) The wall displacement due to geothermal activation is likely to be in the same order of  
572 magnitude with those induced by consolidation only or only with external thermal  
573 solicitations; compared to the thermal effect, the hydro-mechanical coupled effect (e.g.  
574 lateral soil pressure and excess pore water pressure) overwhelmingly dominates the  
575 long-term wall displacement.

576 If seasonal temperature change is considered but without geothermal operation, the  
577 thermal expansion of the slabs inside the station box may push against the retaining  
578 wall and thus induce slight horizontal movement.

579 During geothermal operation inside the diaphragm walls, cyclically seasonal  
580 temperature variation may have an influence on the wall movement particularly near  
581 the ground surface at the connections between the diaphragm walls and the  
582 superstructure due to: i) the temperature gradient along the wall thickness in the lateral  
583 direction and ii) the differential vertical movement during seasonal variations. The  
584 differential wall movement induced by geothermal operation may potentially cause  
585 serviceability problems (e.g. cracks), particularly at the structural connections, for  
586 example, between the wall and the slabs.

587 2) Following seasonal geothermal operation mode assumed in this study, the temperature-  
588 induced ground settlement is unlikely to pose a potential risk to neighbouring buildings  
589 in stiff London clay. Notably, the ground settlement near the station is very sensitive to  
590 the stiffness degradation of the stiff clay due to the additional soil movement induced  
591 by the geothermal operation. For the design of geothermal retaining structure, it is  
592 desired to obtain the soil stiffness properties from the particular construction site rather  
593 than simply referring to past test data elsewhere.

594 3) Although the long-term basement heave is primarily governed by the dissipation of  
595 excess pore water pressure regardless of geothermal operation, it's still necessary to  
596 assess structural performance at the connections between the wall and slabs for  
597 geothermal operation, as to evaluate the risk of cracks and other serviceability problems  
598 caused by thermo-induced additional stress concentration.

599 4) The changes of internal structural forces in the long term are mainly controlled by the  
600 dissipation of excess pore water pressure but less affected by the external thermal  
601 solicitations and geothermal operation. Although geothermal operation can cause some  
602 oscillations of structural forces along the wall and base slab, the magnitude may be  
603 negligible compared against the structural forces generated at the construction stage.

604 In summary, the geothermal operation may have an impact on the long-term mechanical  
605 performance of geothermal diaphragm wall in stiff clay in relation to potential serviceability  
606 issues (e.g. thermal-induced concrete cracks) but not critical safety problems. At present, the  
607 geothermal system of London Dean Street Station is not in operation but experiencing re-design,  
608 and therefore no relevant monitoring data is yet available to validate the long-term geothermal  
609 diaphragm wall behaviour, as stated by the Customer Experience Executive of Transport for  
610 London Customer Services. For future study, there is a high demand of field data in relation to  
611 long-term diaphragm wall behaviour during geothermal operation with particular emphasis on  
612 differential ground movement and serviceability issues (e.g. cracks) at connections between  
613 the wall and slabs. In addition, more detailed aspects will be considered in the further research,  
614 e.g. various thermal operation modes, more thermal loading situations and the arrangement of  
615 heat exchanger pipes in a 3D model.

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621

## 622 **7 Appendix**

623 The short-term model in this paper has been carefully validated with the monitoring data,  
624 nonetheless, it is still necessary to state the reliability of the long-term model in some extent.  
625 Thus, five more models derived from the numerical model of scenario Long-term C have been  
626 conducted to carry out the sensitivity analyses for the evaluation of three major concerns: 1)  
627 thermal properties of concrete elements; 2) various station temperature; 3) and stiffness  
628 degradation boundaries of clayey layers. All the analyses in the appendix are performed with

629 regard to the comparison of horizontal wall movement between the additional model and the  
630 original Long-term C model.

### 631 **7.1 Thermal properties of concrete slabs**

632 As mentioned in Figure 7, the horizontal wall movement is significantly influenced by the  
633 thermal expansion of the concrete slabs. Rui (2014) pointed out that the thermal expansion  
634 coefficient of concrete material determines the thermal strain of the concrete elements and the  
635 displacements. In this study, a sensitivity analysis on this property is evaluated by comparing  
636 the effect of three different thermal expansion coefficients of concrete slabs on the wall  
637 behaviour, including zero thermal expansion coefficient, thermal expansion coefficient  $\alpha =$   
638  $1 \times 10^{-5}$  1/K (original Long-term C model) and  $\alpha = 4 \times 10^{-5}$  1/K.

639 Figure 20 compares the horizontal wall movement with different concrete thermal expansion  
640 coefficients. Without the effect of thermal expansion from concrete slabs ( $\alpha = 0$ ), the wall is  
641 generally pushed towards the excavation side as shown in Figure 20(b). Compared to the case  
642 with thermal expansion  $\alpha = 1 \times 10^{-5}$  1/K (original Long-term C model), the maximum difference  
643 between the case with  $\alpha = 0$  and the original one with  $\alpha = 1 \times 10^{-5}$  1/K is 1.8 mm, appearing  
644 between Slab 1 and Slab 2, and the minimum difference is as small as 0.1 mm at the toe of the  
645 diaphragm wall. The effect of thermal volume expansion of the concrete slabs on the horizontal  
646 wall movement is relatively uniform along the wall at the station side, whilst the induced wall  
647 deflection difference between the two cases becomes less obvious at the lower part of the wall  
648 far below the base slab. On the contrary, Figure 20(c) presents the incremental horizontal wall  
649 movement by adopting a 4 times greater thermal expansion coefficient of the concrete slabs ( $\alpha$   
650  $= 4 \times 10^{-5}$ ) than the original coefficient ( $\alpha = 1 \times 10^{-5}$  1/K). The bigger thermal expansion  
651 coefficient is, the greater the thermal expansion volume of the concrete slabs would be, and as  
652 such the wall is significantly pushed towards the soil side, with the maximum magnitude of 4.2  
653 mm between Slab 1 and Base Slab. After 30 years of thermal operation, the differences between  
654 the two cases are becoming even smaller both near the toe of the wall and the part of wall  
655 between Slab 2 and Slab 1 within 0.3 mm. As discussed earlier, the horizontal wall deflection  
656 is contributed by hydro-mechanical effects (e.g. lateral soil pressure and excess pore water  
657 pressure), resisting forces of slabs and thermal effects (e.g. thermal expansion of the concrete  
658 wall and slabs). It is noted that the effect of thermal expansion of the concrete slabs on the  
659 horizontal wall movement is not constantly expanding with the thermal expansion coefficient  
660 but compensated by other aspects.

661 In summary, the thermal expansion force from the slabs inside the station pushes the retaining  
662 wall towards the soil side, and the larger thermal expansion coefficient of the concrete slabs is  
663 the greater wall movement would be. As soil consolidates with time, the other influencing  
664 factors (e.g. lateral soil pressure, propping force of the slabs) become more significant with  
665 time, whereas the effect of slab thermal expansion on horizontal wall movement relatively  
666 weakens.

## 667 7.2 Station temperature

668 For simplicity, all the thermal boundaries along the wall at the excavation side and the thermal  
669 boundaries of the slabs are represented by a uniform station temperature, assuming that the  
670 station temperature at the operation stage is kept constant by air ventilation system. In this  
671 study, a dedicated sensitivity analysis is conducted to evaluate the effect of station temperature  
672 on the D-wall behaviour including three scenarios: 4°C (lower bound as the air temperature in  
673 winter), 18°C (typical indoor temperature in a station as the original Long-term C model) and  
674 23°C (upper bound as the air temperature in summer).

675 The temperature-induced horizontal wall movement in Long-term C is shown in Figure 21.  
676 The station temperature in Figure 21(a) is set constantly at 4°C, generating less thermal  
677 expansion for the concrete slabs and leading the wall to move significantly towards the  
678 excavation side, in comparison with the original model with the 18°C of station temperature.  
679 Unlike the original model, the horizontal wall movements near the ground surface reveals no  
680 obvious trend towards the soil side in winters, as a result of no temperature difference  
681 development along the wall thickness in winters (4°C near the soil side and 4°C near the station  
682 side). On the contrary, a higher constant station temperature (23°C) would push the part of the  
683 wall near the ground surface more towards the soil side than the original model, with regard to  
684 a 19°C temperature difference along the wall thickness direction in winters (4°C near the soil  
685 side and 23°C near the station side), as shown in Figure 21(b). In general, the station  
686 temperature variation in Figure 21(b) is only 5°C less than it in Figure 21(a) (14°C), as a result,  
687 the maximum horizontal wall movement difference obtained in 30 years is about 1.4 mm in  
688 Figure 21(b), much less than it in Figure 21(a) (3.9 mm). Besides, the bending lateral deflection  
689 of the wall near the ground surface in the model with 23°C of station temperature is about 0.9  
690 mm, greater than that of 0.7 mm in the original model, as the temperature difference along the  
691 thickness of the wall is 5°C higher than the original model.



692 In summary, the change of temperature range for the thermal boundaries inside the station  
693 indicates that the higher the station temperature is, the more horizontal wall movement towards  
694 the soil side would be, which is dominated by the thermal expansion of the concrete slabs than  
695 the wall thermal bending effect. The temperature variation along the wall at the station side  
696 mainly contributes to the bending deflection of the wall near the ground surface.

### 697 **7.3 High stiffness modulus of clayey layers**

698 To better understand the wall displacement, an additional model with remarkably higher  
699 stiffness modulus for clayey layers is analysed in this section. The soil properties of the clay  
700 layers for both the higher stiffness model parameters and original parameters in HSS models  
701 are listed in Table 6. The performance of HSS models with both the original model parameters  
702 and higher stiffness are compared against experimental data from other sites available in  
703 literature, respectively, as shown in Figure 22: the HSS soil models in original model match  
704 with the experimental data, while the results from the additional model shows higher stiffness  
705 than the experimental curves, as expected.

706 Figure 23 shows the short-term model validation between the original model and higher  
707 stiffness bound HSS model. Although the validation near the excavation surface is slightly  
708 improved, there still exists obvious wall deflection at the toe of the wall. As the shear stiffness  
709 at the higher strain range is low, the wall displacement due to excavation can still be  
710 considerable. In addition, as base slab heaves after soil excavation, the wall below the base slab  
711 has to move towards the excavation side according to Terzaghi (1943)'s theory of rigid body  
712 movement below a foundation. Figure 24 shows the incremental horizontal wall movement in  
713 Long-term C with higher stiffness bound of HSS soil models. The deflection for the part of  
714 wall between Slab 2 and Slab 1 in this model is very similar to the original model, while the  
715 wall movements towards the excavation side above Slab 2 and below Base Slab in the long  
716 term are reduced by about 1.3 mm.

717 In summary, the short-term model validation can be improved and the long-term horizontal  
718 wall movements can be reduced by significantly increasing the HSS soil stiffness modulus.  
719 Nevertheless, there is no evidence for such high stiff clayey layers on site in practice as the  
720 green curves plotted in Figure 22.

721

722

723 **8 References**

- 724 ADAM, D. & MARKIEWICZ, R. 2009. Energy from earth-coupled structures, foundations, tunnels  
725 and sewers. *Geotechnique*, 59, 229-236.
- 726 AMIS, T., ROBINSON, C. & WONG, S. 2010. Intergrating geothermal loops into the diaphragm  
727 walls of the Knightsbridge Palace Hotel project. *In Proc. 11th DFI/EFFC Int. Conf.*  
728 *Geotechnical Challenges in Urban Regeneration*. London.
- 729 BARLA, M., DI DONNA, A. & SANTI, A. 2018. Energy and mechanical aspects on the thermal  
730 activation of diaphragm walls for heating and cooling. *Renewable Energy*.
- 731 BOURNE-WEBB, P., AMATYA, B., SOGA, K., AMIS, T., DAVIDSON, C. & PAYNE, P. 2009. Energy  
732 pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile  
733 response to heat cycles. *Geotechnique*, 59, 237-248.
- 734 BOURNE-WEBB, P., BURLON, S., JAVED, S., KURTEN, S. & LOVERIDGE, F. 2016. Analysis and  
735 design methods for energy geostructures. *Renewable & Sustainable Energy Reviews*,  
736 65, 402-419.
- 737 BRANDL, H. 1998. Energy piles and diaphragm walls for heat transfer from and into the ground.  
738 *Deep Foundations on Bored and Auger Piles - Bap lii*, 37-60.
- 739 BRANDL, H. 2006. Energy foundations and other thermo-active ground structures.  
740 *Geotechnique*, 56, 81-122.
- 741 BRINKGREVE, R. B. J., KUMARSWAMY, S., SWOLFS, W. M. & FORIA, F. 2018. *PLAXIS 2D*  
742 *Reference Manual Version 2018*, Delft, PLAXIS.
- 743 BURLAND, J. B. & WROTH, C. P. 1975. Settlement of buildings and associated damage.  
744 *Proceedings, British Geotechnical Society Conference on Settlement of Structures*,  
745 *Cambridge*. Cambridge: Pentech Press.
- 746 CABARKAPA, Z., MILLIGAN, G. W. E., MENKITI, C. O., MURPHY, J. & POTTS, D. M. 2003. Design  
747 and performance of a large diameter shaft in Dublin Boulder Clay. *Bga International*  
748 *Conference on Foundations: Innovations, Observations, Design and Practice*, 175-185.
- 749 CHAN, D., MADABHUSHI, S., NICHOLSON, D., CHAPMAN, T. & SOLERA, S. 2018. *Technical Paper:*  
750 *Twenty-one Years of Heave Monitoring in London Clay at Horseferry Road Basement*  
751 [Online]. Ground Engineering. Available: [https://www.geplus.co.uk/technical-](https://www.geplus.co.uk/technical-papers/technical-paper-twenty-one-years-of-heave-monitoring-in-london-clay-at-horseferry-road-basement/10035934.article?search=https%3a%2f%2fwww.geplus.co.uk%2fsearcharticles%3fqsearch%3d1%26keywords%3dheave+monitoring+in+london)  
752 [papers/technical-paper-twenty-one-years-of-heave-monitoring-in-london-clay-at-](https://www.geplus.co.uk/technical-papers/technical-paper-twenty-one-years-of-heave-monitoring-in-london-clay-at-horseferry-road-basement/10035934.article?search=https%3a%2f%2fwww.geplus.co.uk%2fsearcharticles%3fqsearch%3d1%26keywords%3dheave+monitoring+in+london)  
753 [horseferry-road-](https://www.geplus.co.uk/technical-papers/technical-paper-twenty-one-years-of-heave-monitoring-in-london-clay-at-horseferry-road-basement/10035934.article?search=https%3a%2f%2fwww.geplus.co.uk%2fsearcharticles%3fqsearch%3d1%26keywords%3dheave+monitoring+in+london)  
754 [basement/10035934.article?search=https%3a%2f%2fwww.geplus.co.uk%2fsearcharti](https://www.geplus.co.uk/technical-papers/technical-paper-twenty-one-years-of-heave-monitoring-in-london-clay-at-horseferry-road-basement/10035934.article?search=https%3a%2f%2fwww.geplus.co.uk%2fsearcharticles%3fqsearch%3d1%26keywords%3dheave+monitoring+in+london)  
755 [cles%3fqsearch%3d1%26keywords%3dheave+monitoring+in+london](https://www.geplus.co.uk/technical-papers/technical-paper-twenty-one-years-of-heave-monitoring-in-london-clay-at-horseferry-road-basement/10035934.article?search=https%3a%2f%2fwww.geplus.co.uk%2fsearcharticles%3fqsearch%3d1%26keywords%3dheave+monitoring+in+london) [Accessed  
756 04/12/2018 2018].
- 757 CHAN, D. Y. K. & MADABHUSHI, S. P. G. 2017. Designing urban deep basements in South East  
758 England for future ground movement - Progress and opportunities for experimental  
759 simulation of long-term heave. *International Symposium for Next Generation*  
760 *Infrastructure*. London.

- 761 COLETTI, A. & STERPI, D. 2016. Structural and geotechnical effects of thermal loads in energy  
762 walls. *Vi Italian Conference of Researchers in Geotechnical Engineering, Cnrig2016 -*  
763 *Geotechnical Engineering in Multidisciplinary Research: From Microscale to Regional*  
764 *Scale*, 158, 224-229.
- 765 DI DONNA, A., CECINATO, F., LOVERIDGE, F. & BARLA, M. 2017. Energy performance of  
766 diaphragm walls used as heat exchangers. *Proceedings of the Institution of Civil*  
767 *Engineers-Geotechnical Engineering*, 170, 232-245.
- 768 DONG, S., LI, X., MINH TANG, A., MICHEL PEREIRA, J., TRI NGUYEN, V., CHE, P. & XIONG, Z. 2018.  
769 Thermo-mechanical behaviour of energy diaphragm wall: physical and numerical  
770 modelling. *Applied Thermal Engineering*.
- 771 GABA, A., SIMPSON, B., POWRIE, W. & BEADMAN, D. 2003. *CIRIA C580 Embedded retaining*  
772 *walls - guidance for economic design*, London, CIRIA.
- 773 GASHTI, E., MALASKA, M. & KUJALA, K. 2014. Evaluation of thermo-mechanical behaviour of  
774 composite energy piles during heating/cooling operations. *Engineering Structures*, 75,  
775 363-373.
- 776 GASPARRE, A. 2005. *Advanced Laboratory Characterisation of London Clay*. PhD thesis,  
777 Imperial College London.
- 778 HIGHT, D. W., ELLISON, R. A. & PAGE, D. P. 2004. *Engineering in the Lambeth Group*, London,  
779 CIRIA.
- 780 HOUSTON, S. L., HOUSTON, W. N. & WILLIAMS, N. D. 1985. Thermo-Mechanical  
781 Behavior of Seafloor Sediments. 111, 1249-1263.
- 782 HSIEH, P. G., OU, C. Y. & HSIEH, W. H. 2016. Efficiency of excavations with buttress walls in  
783 reducing the deflection of the diaphragm wall. *Acta Geotechnica*, 11, 1087-1102.
- 784 JEONG, S., LIM, H., LEE, J. K. & KIM, J. 2014. Thermally induced mechanical response of energy  
785 piles in axially loaded pile groups. *Applied Thermal Engineering*, 71, 608-615.
- 786 KNELLWOLF, C., PERON, H. & LALOUI, L. 2011. Geotechnical Analysis of Heat Exchanger Piles.  
787 *Journal of Geotechnical and Geoenvironmental Engineering*, 137, 890-902.
- 788 LALOUI, L., NUTH, M. & VULLIET, L. 2006. Experimental and numerical investigations of the  
789 behaviour of a heat exchanger pile. *International Journal for Numerical and Analytical*  
790 *Methods in Geomechanics*, 30, 763-781.
- 791 LIM, A., OU, C. Y. & HSIEH, P. G. 2018. Investigation of the integrated retaining system to limit  
792 deformations induced by deep excavation. *Acta Geotechnica*, 13, 973-995.
- 793 LINGNAU, B. E., GRAHAM, J. & TANAKA, N. 1995. Isothermal modeling of sand-bentonite  
794 mixtures at elevated temperatures. *Canadian Geotechnical Journal*, 32, 78-88.
- 795 MILIZIANO, S. 1992. *Influenza della temperatura sul comportamento meccanico delle terre*  
796 *coesive*. Tesi di Dottorato in Ingegneria Geotecnica, Università di Roma "La Sapienza".
- 797 MIMOUNI, T. & LALOUI, L. 2015. Behaviour of a group of energy piles. *Canadian Geotechnical*  
798 *Journal*, 52, 1913-1929.
- 799 NISHA, J. J. & MUTTHARAM, M. 2017. Deep Excavation Supported by Diaphragm Wall: A Case  
800 Study. *Indian Geotechnical Journal*, 47, 373-383.

- 801 NOAA. 2018. *London weather averages* [Online]. National Centers for Environmental  
802 Information. Available: <https://www.ncdc.noaa.gov/> [Accessed 01/11/2018 2018].
- 803 OU, C. Y. & HSIEH, P. G. 2011. A simplified method for predicting ground settlement profiles  
804 induced by excavation in soft clay. *Computers and Geotechnics*, 38, 987-997.
- 805 OU, C. Y. & LAI, C. H. 1994. Finite-Element Analysis of Deep Excavation in Layered Sandy and  
806 Clayey Soil Deposits. *Canadian Geotechnical Journal*, 31, 204-214.
- 807 OUYANG, Y. 2014. *Geotechnical behaviour of energy piles*. PhD Thesis, University of  
808 Cambridge.
- 809 RAMMAL, D. 2017. *Thermal-mechanical behaviour of geothermal structures: numerical*  
810 *modelling and recommendations*. PhD Thesis, University of Lille 1 Sciences et  
811 Technologies.
- 812 RAMMAL, D., HROUEH, H., BURLON, S. & SURYATRIYASTUTI, M. E. Numerical study of the  
813 performance of energy diaphragm walls. In: WUTTKE, B. S., ed. *Energy Geotechnics*,  
814 2016 London. Taylor & Francis Group.
- 815 RAMMAL, D., MROUEH, H. & BURLON, S. 2018. Impact of thermal solicitations on the design  
816 of energy piles. *Renewable & Sustainable Energy Reviews*, 92, 111-120.
- 817 RUI, Y. 2014. *Thermo-hydro-mechanical coupling analysis of a thermo-active diaphragm wall*.  
818 PhD Thesis, University of Cambridge.
- 819 RUI, Y. & YIN, M. 2018. Thermo-hydro-mechanical coupling analysis of a thermo-active  
820 diaphragm wall. *Canadian Geotechnical Journal*, 55, 720-735.
- 821 SCHWAMB, T. 2014. *Performance Monitoring and Numerical Modelling of a Deep Circular*  
822 *Excavation*. PhD Thesis, University of Cambridge.
- 823 STERPI, D., ANGELOTTI, A., CORTI, D. & RAMUS, M. Numerical analysis of heat transfer in  
824 thermo-active diaphragm walls. In: HICKS, B., ROHE, ed. *Numerical Methods in*  
825 *Geotechnical Engineering*, 2014 London. Taylor & Francis Group.
- 826 STERPI, D., COLETTI, A. & MAURI, L. 2017. Investigation on the behaviour of a thermo-active  
827 diaphragm wall by thermo-mechanical analyses. *Geomechanics for Energy and the*  
828 *Environment*, 9, 1-20.
- 829 SUN, M., XIA, C. C. & ZHANG, G. Z. 2013. Heat transfer model and design method for  
830 geothermal heat exchange tubes in diaphragm walls. *Energy and Buildings*, 61, 250-  
831 259.
- 832 SURYATRIYASTUTI, M. E., MROUEH, H. & BURLON, S. 2012. Understanding the temperature-  
833 induced mechanical behaviour of energy pile foundations. *Renewable & Sustainable*  
834 *Energy Reviews*, 16, 3344-3354.
- 835 TERZAGHI, K. 1943. *Theoretical Soil Mechanics*, New York, Wiley.
- 836 WONGSAROJ, J. 2005. *Three-dimensional finite element analysis of short and long-term ground*  
837 *response to open-face tunnelling in stiff clay*. PhD Thesis, University of Cambridge.
- 838 XIA, C. C., SUN, M., ZHANG, G. Z., XIAO, S. G. & ZOU, Y. C. 2012. Experimental study on  
839 geothermal heat exchangers buried in diaphragm walls. *Energy and Buildings*, 52, 50-  
840 55.

841 ZDRAVKOVIC, L., POTTS, D. M. & JOHN, H. D. S. 2005. Modelling of a 3D excavation in finite  
842 element analysis. *Géotechnique*, 55, 497-513.

843

844 **NOTATATIONS**

845	C	Cohesion
846	$C_s$	Specific heat capacity
847	E	Stiffness
848	$E_{50}^{ref}$	Secant stiffness in standard drained triaxial test
849	$E_{oed}^{ref}$	Tangent stiffness for primary oedometer loading
850	$E_{ur}^{ref}$	Unloading / reloading stiffness
851	EA	Normal stiffness of props
852	$D_e$	External diameter of props
853	GHE	Ground heat exchanger
854	$G_0^{ref}$	Reference shear modulus at very small strains
855	$G_s$	Secant stiffness shear modulus
856	HM	Hydro-mechanical analysis
857	HSS	Hardening soil model with small-strain stiffness
858	k	Permeability coefficient
859	$K_o$	Lateral pressure ratio
860	L	the distance between the edge of the station and the very settled ground
861	LMC	Upper Mottled Clay
862	m	Power for stress-level dependency of stiffness
863	M	Bending moment
864	MC	Mohr-Coulomb model
865	N	Normal force

866	$p^{\text{ref}}$	Reference stress for stiffness
867	Q	Shear force
868	$R_f$	Failure ratio $q_f / q_a$ (default $R_f = 0.9$ )
869	TH	Thermo-mechanical analysis
870	THM	Thermo-hydro-mechanical analysis
871	UMC	Upper Mottled Clay
872	2D	Two-dimensional
873	3D	Three-dimensional
874	$\Delta$	Relative settlement between the edge of the station and the very settled ground
875	$\Delta/L$	Settlement assessment ratio
876	$\gamma$	Material weight
877	$\gamma_{0.7}$	Threshold shear stain at which $G_s = 0.72G_0$
878	$\nu$	Poisson's ratio
879	$\lambda_s$	Thermal conductivity
880	$\rho_s$	Soil density
881	$\phi$	Friction angle
882	$\psi$	Tension cut-off and tensile strength
883	$\alpha$	Thermal expansion coefficient

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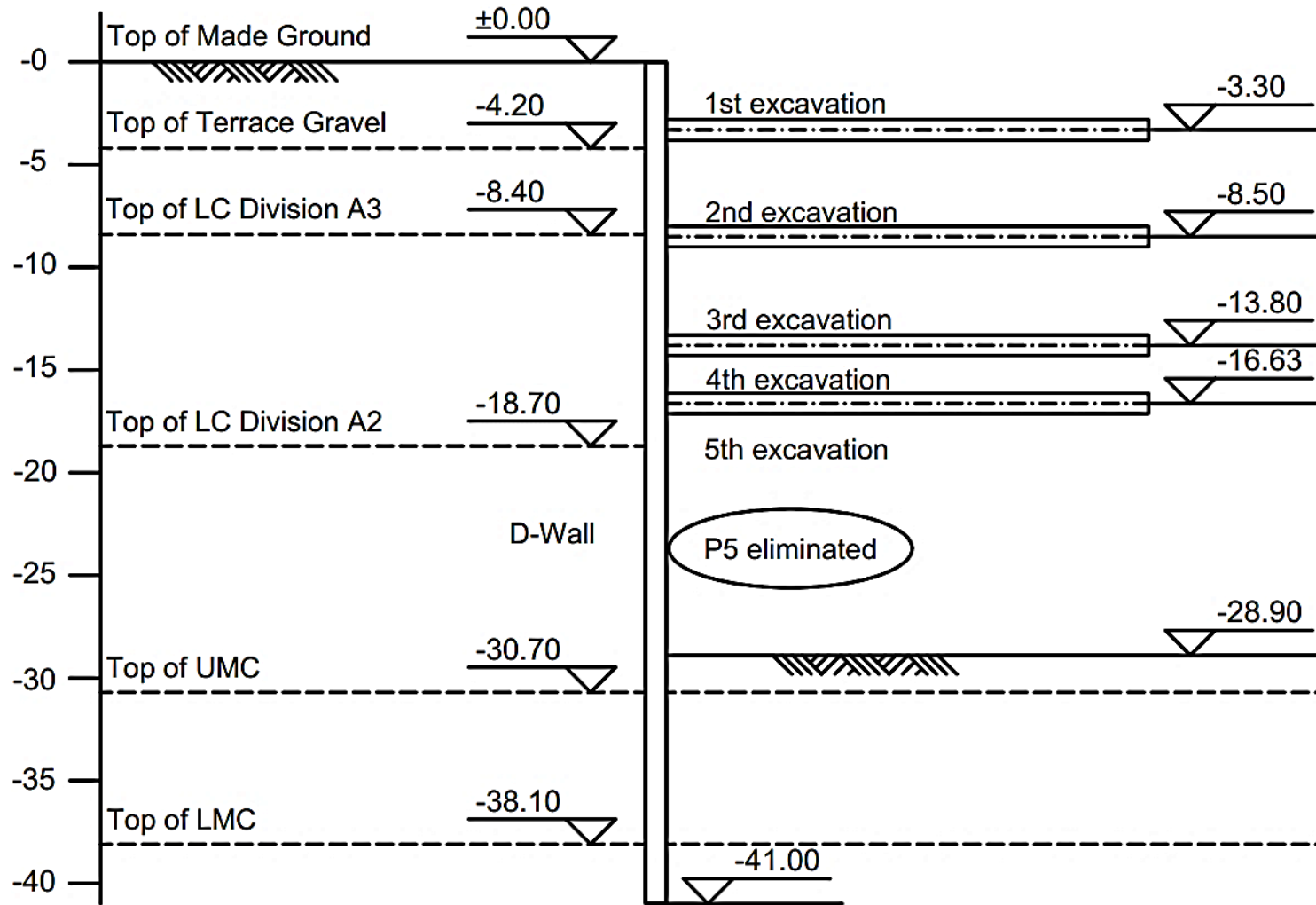


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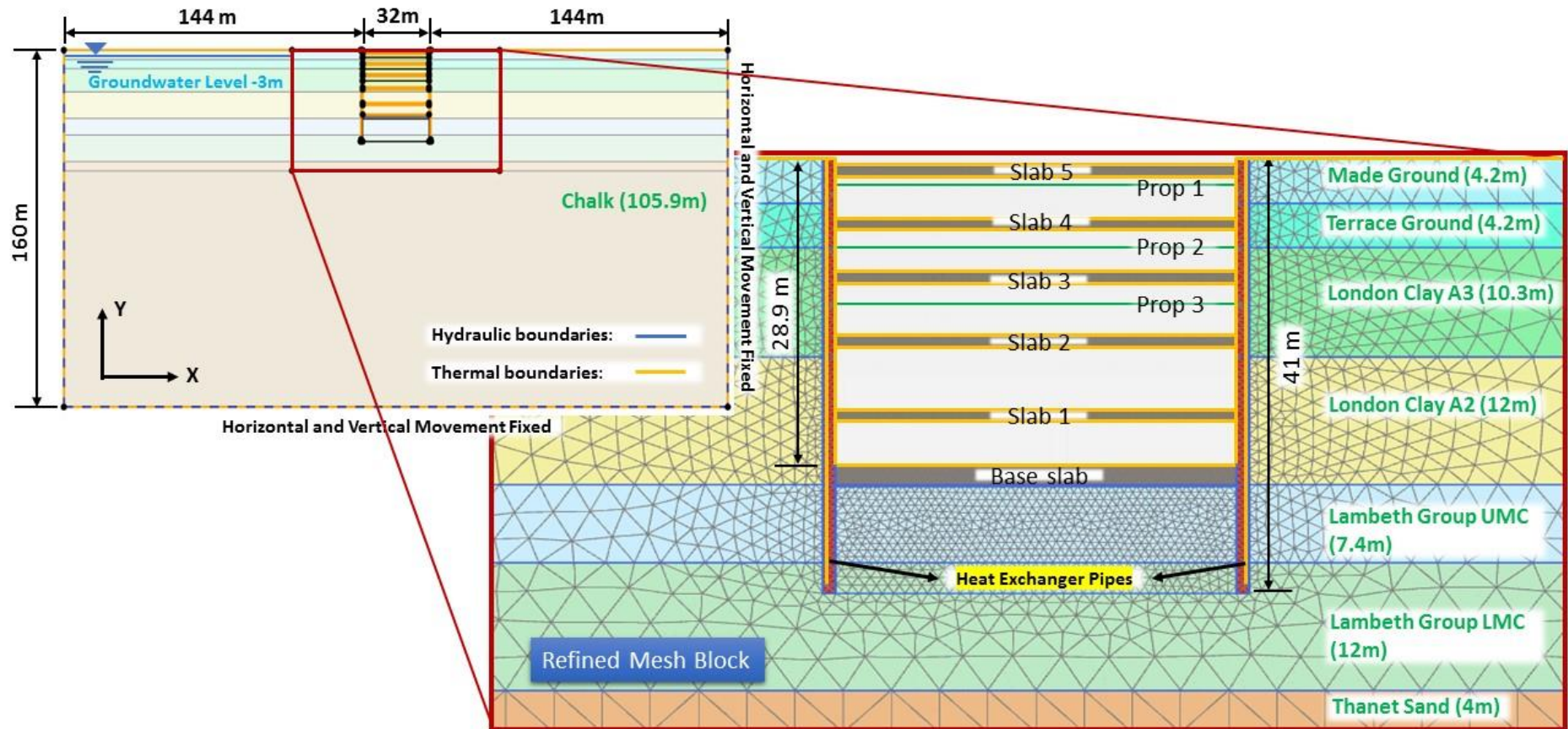


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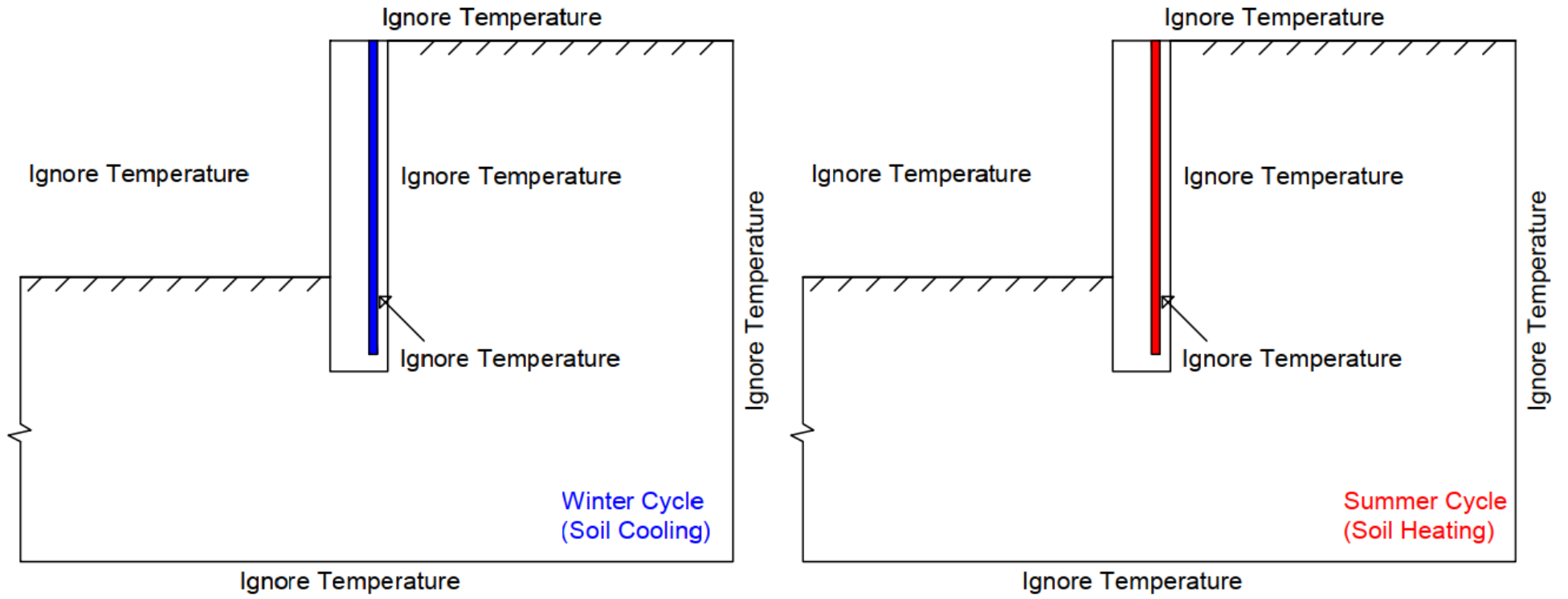




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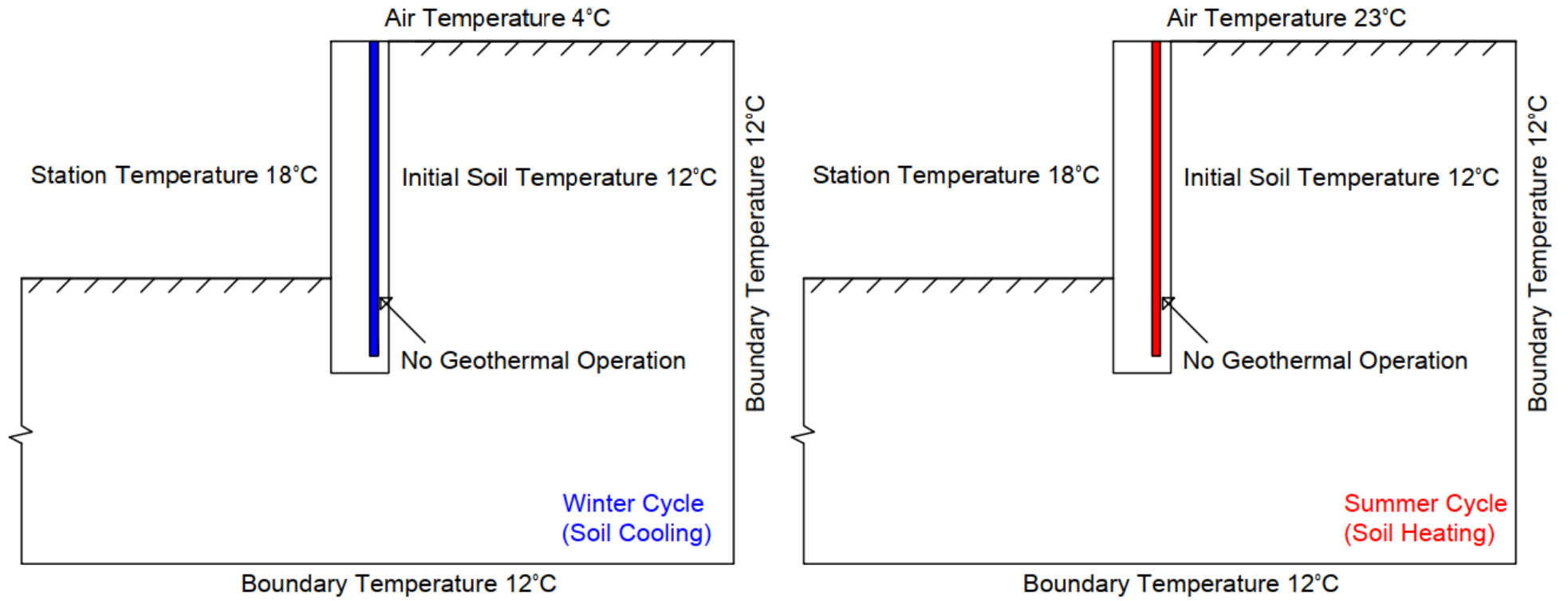


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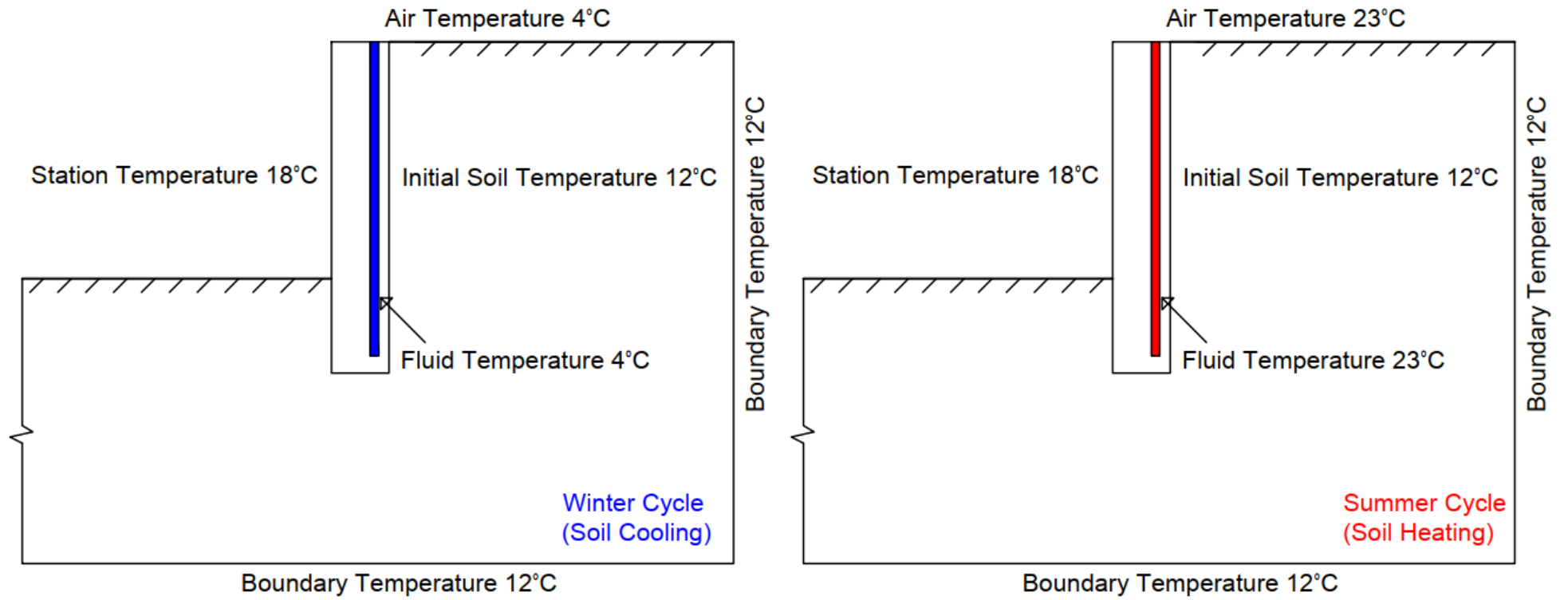


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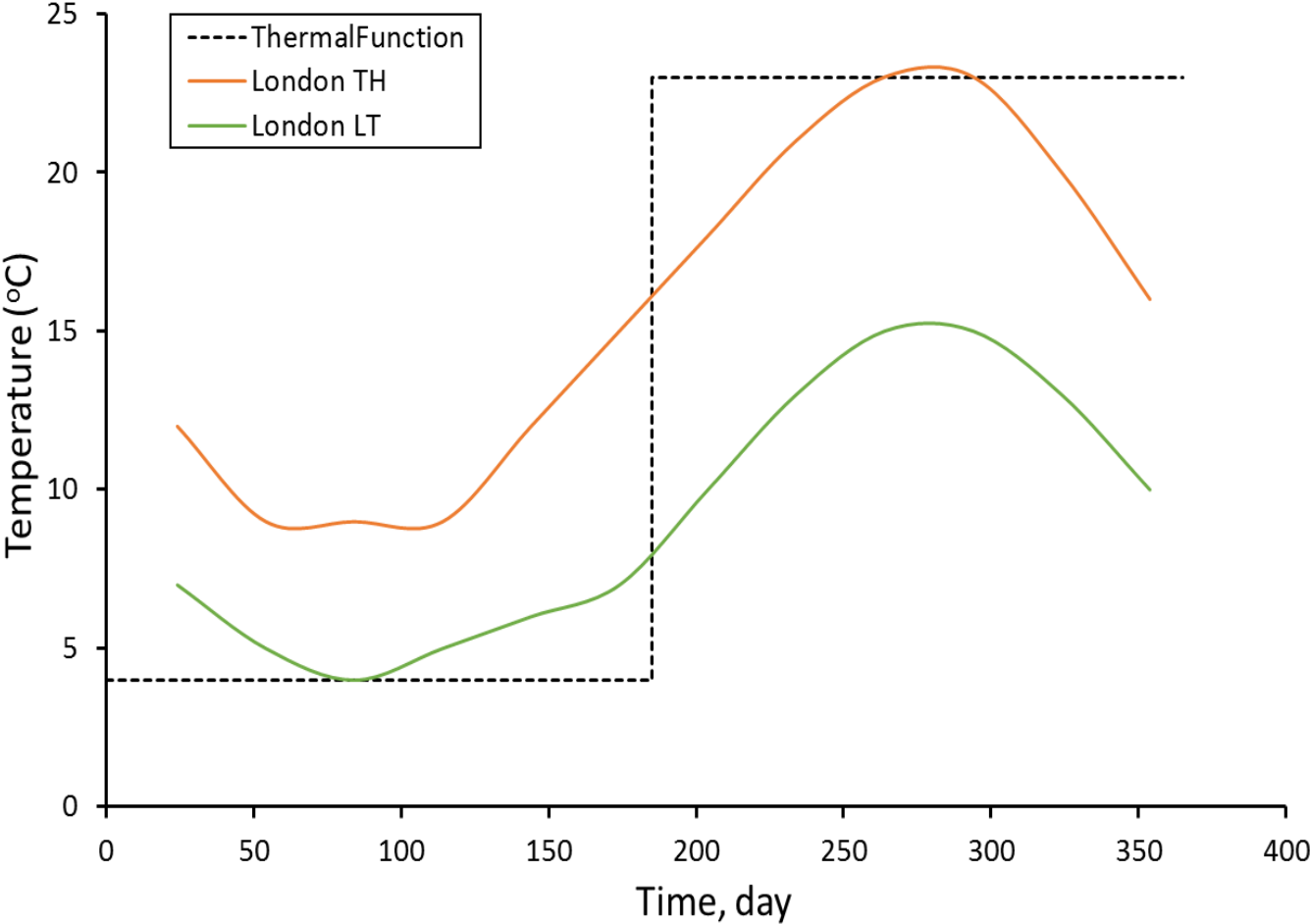


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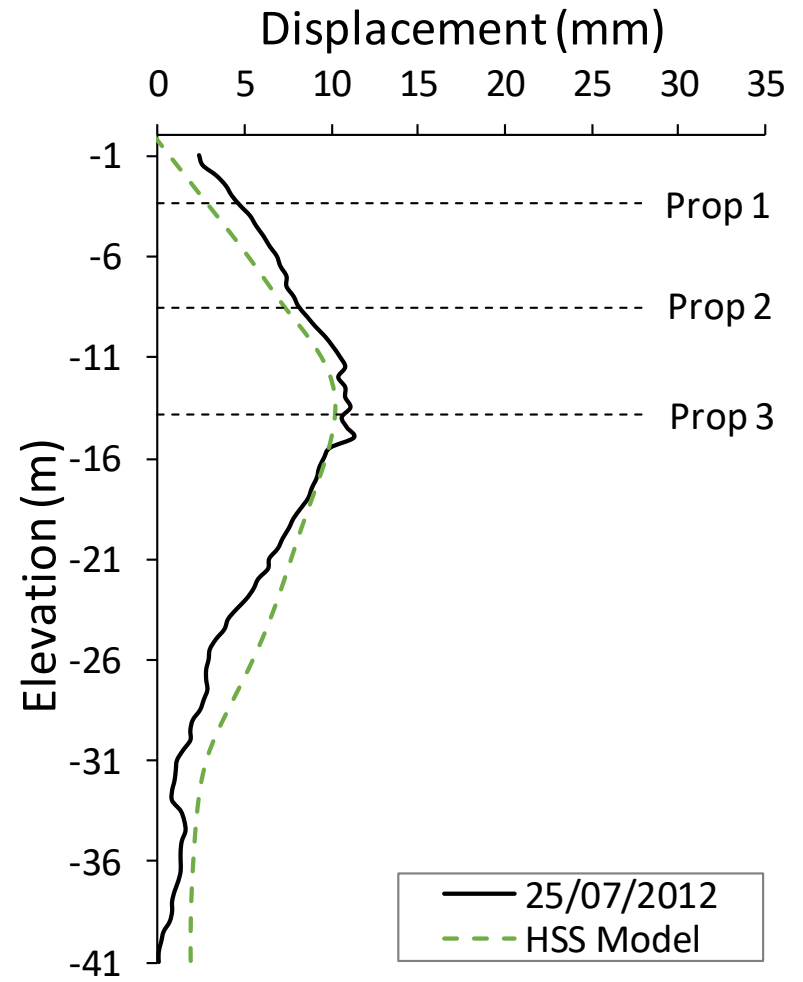
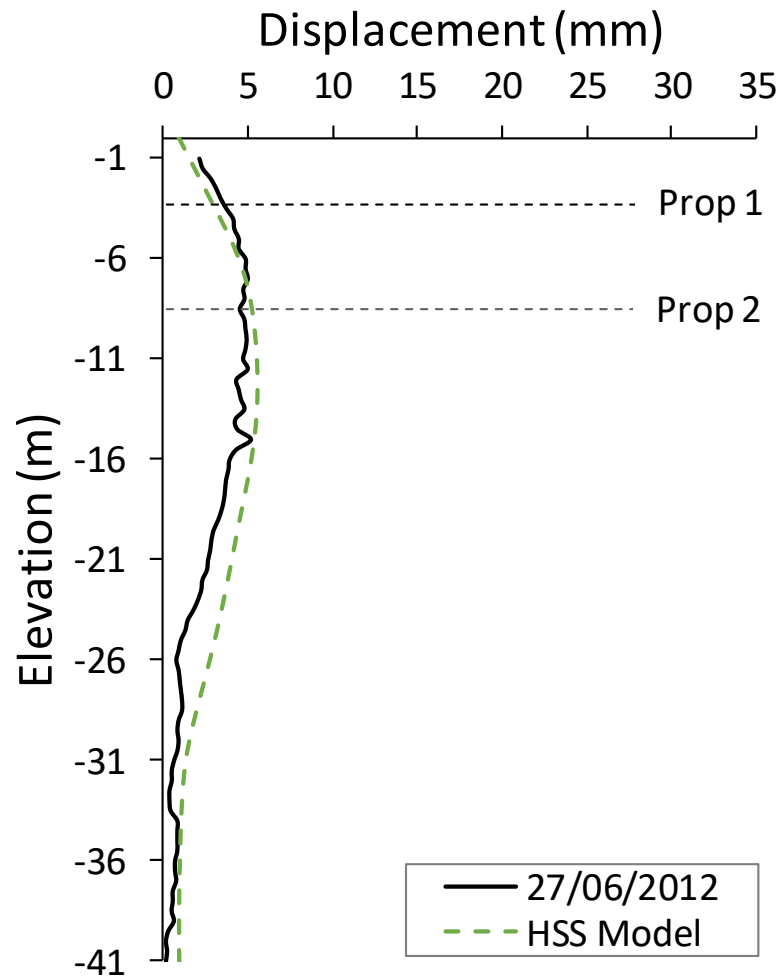


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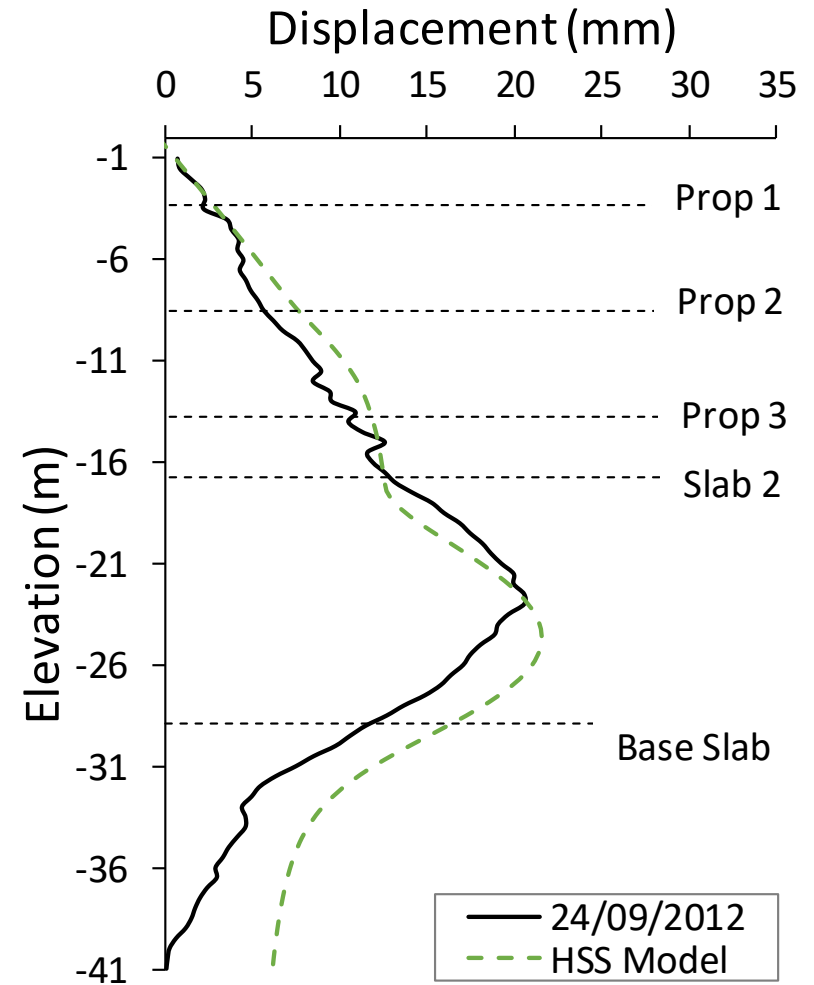
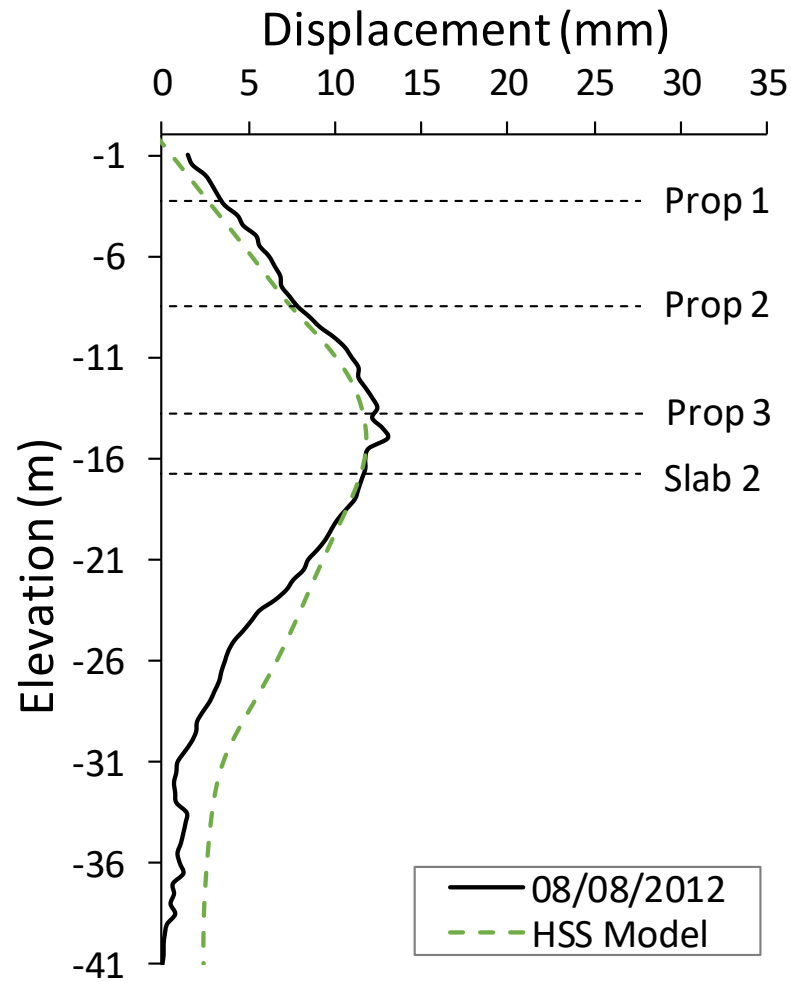


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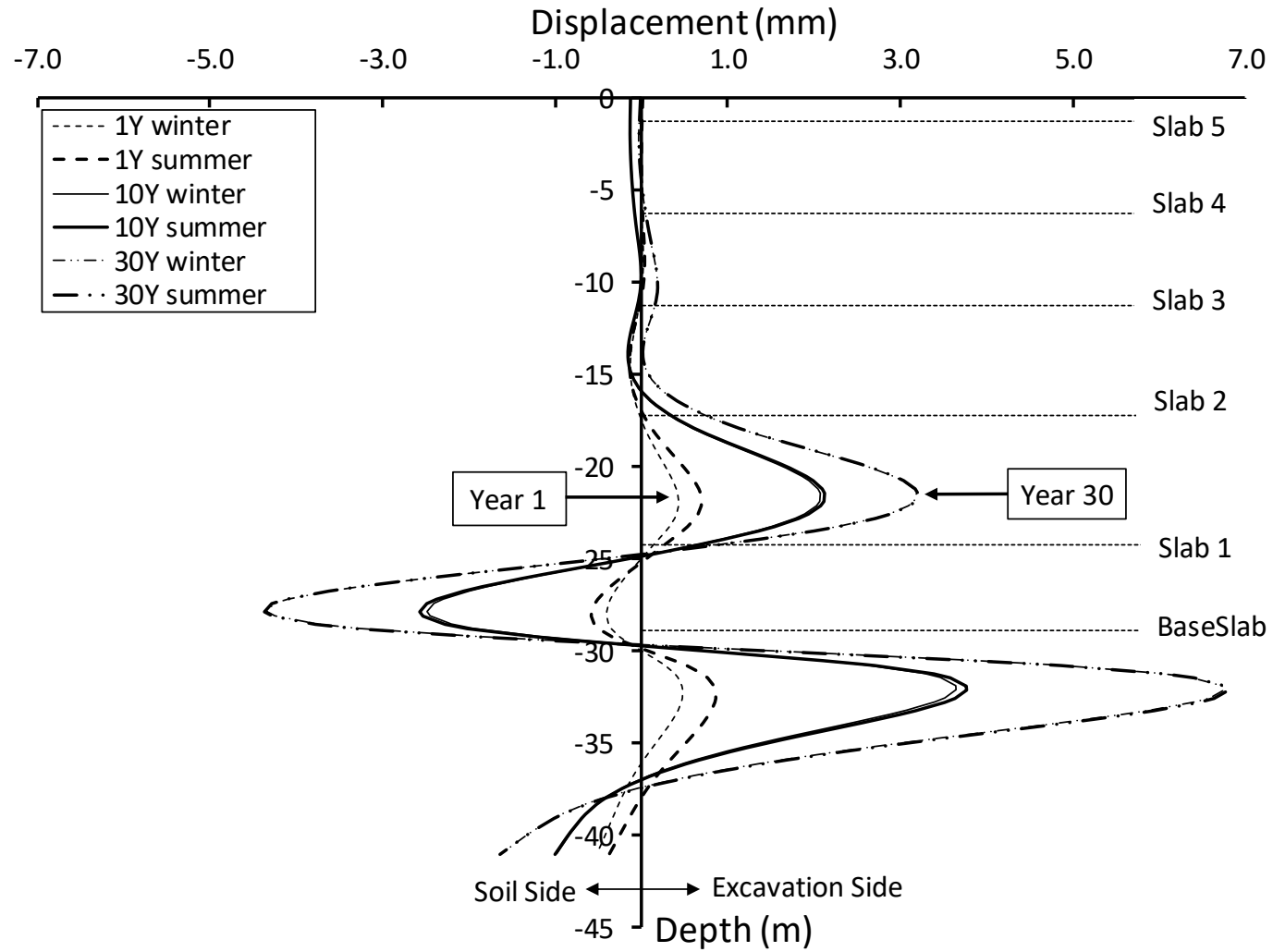


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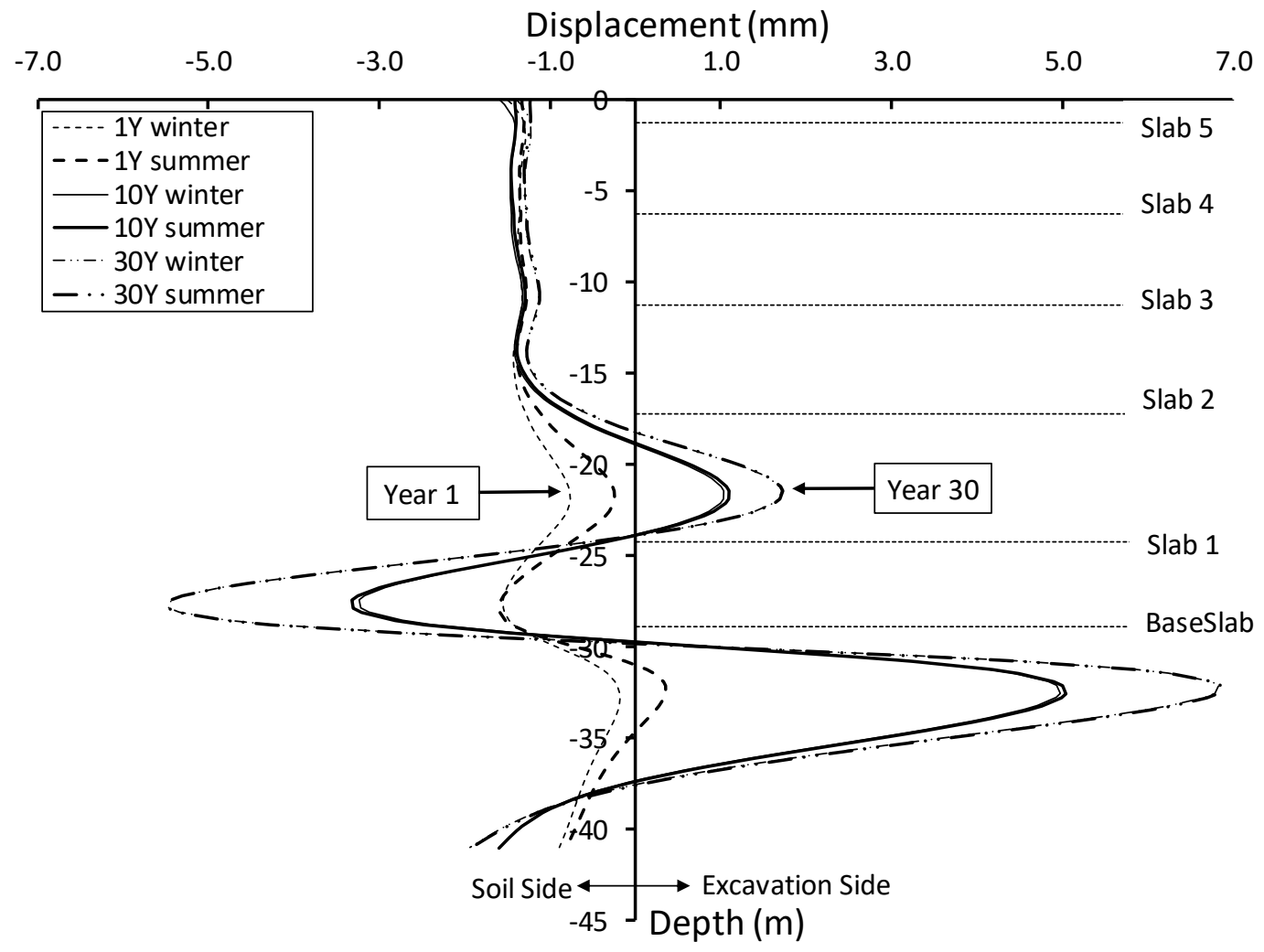


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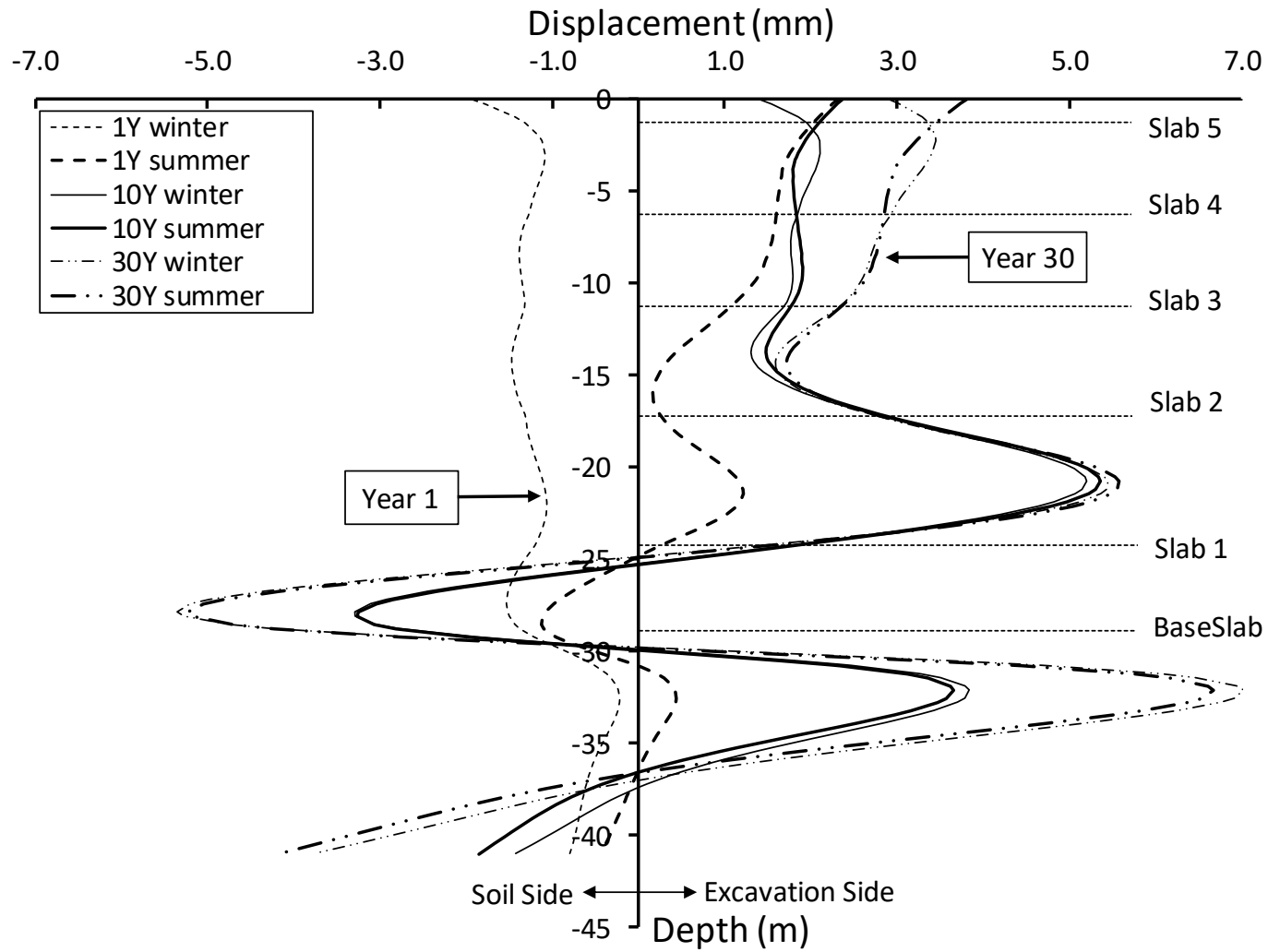




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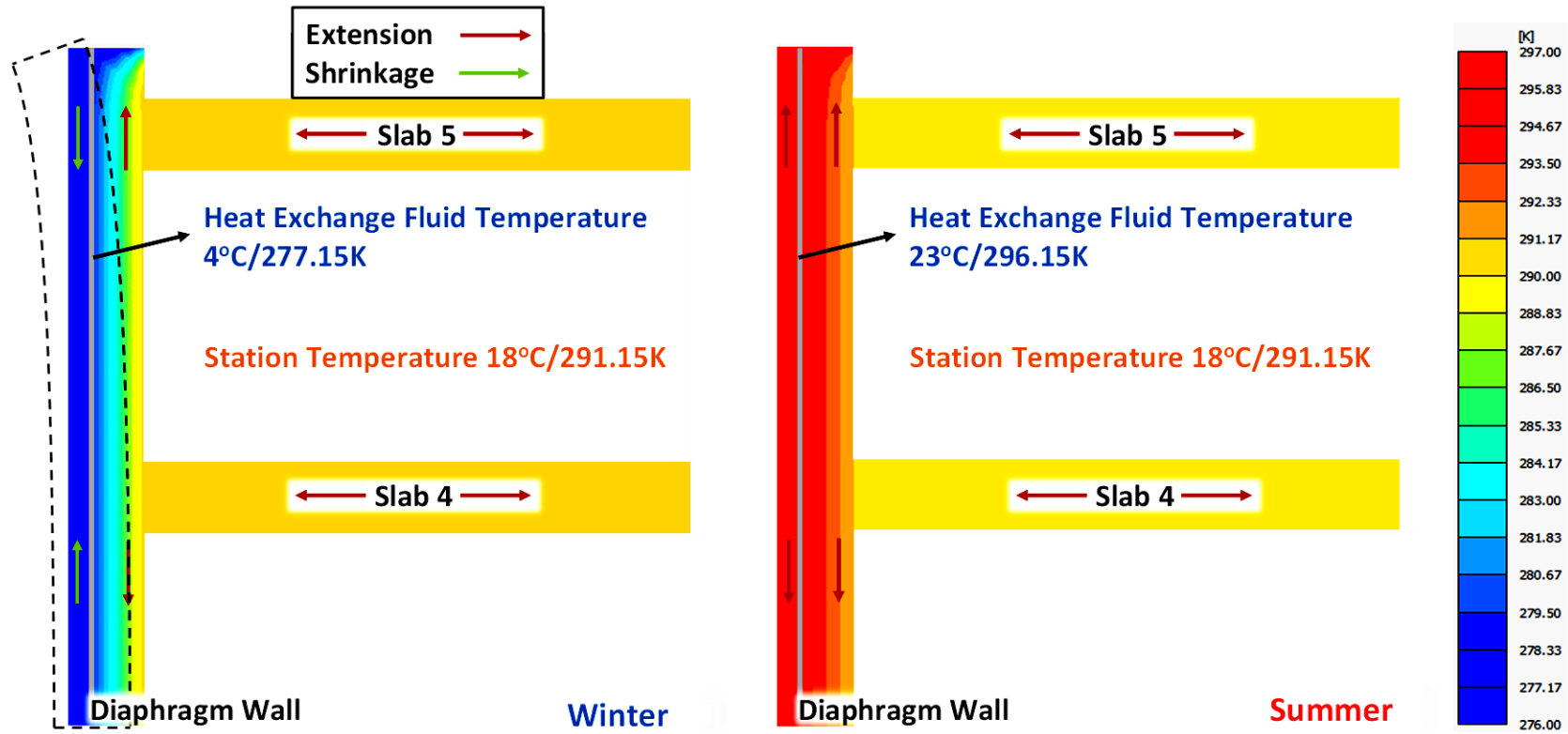


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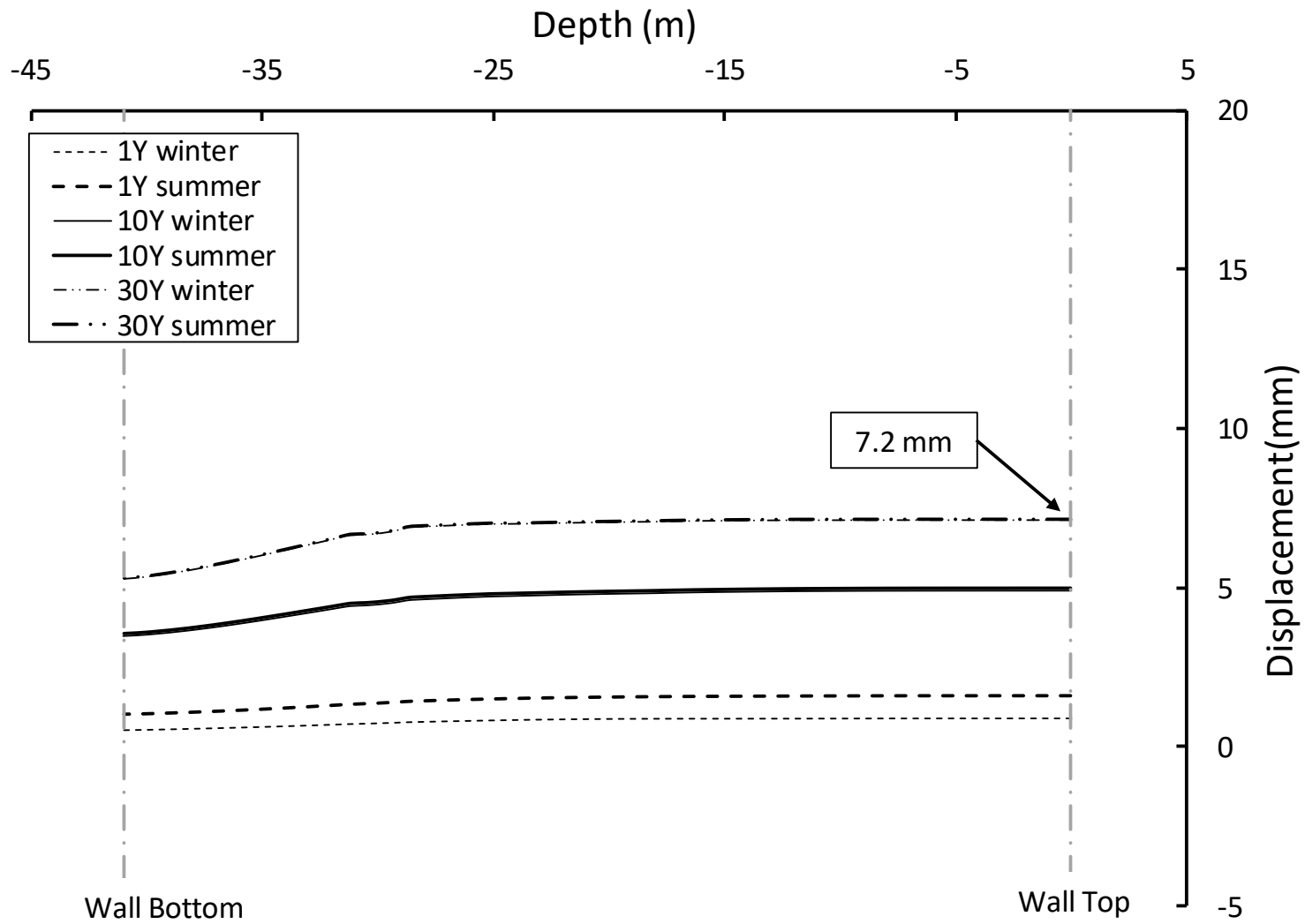


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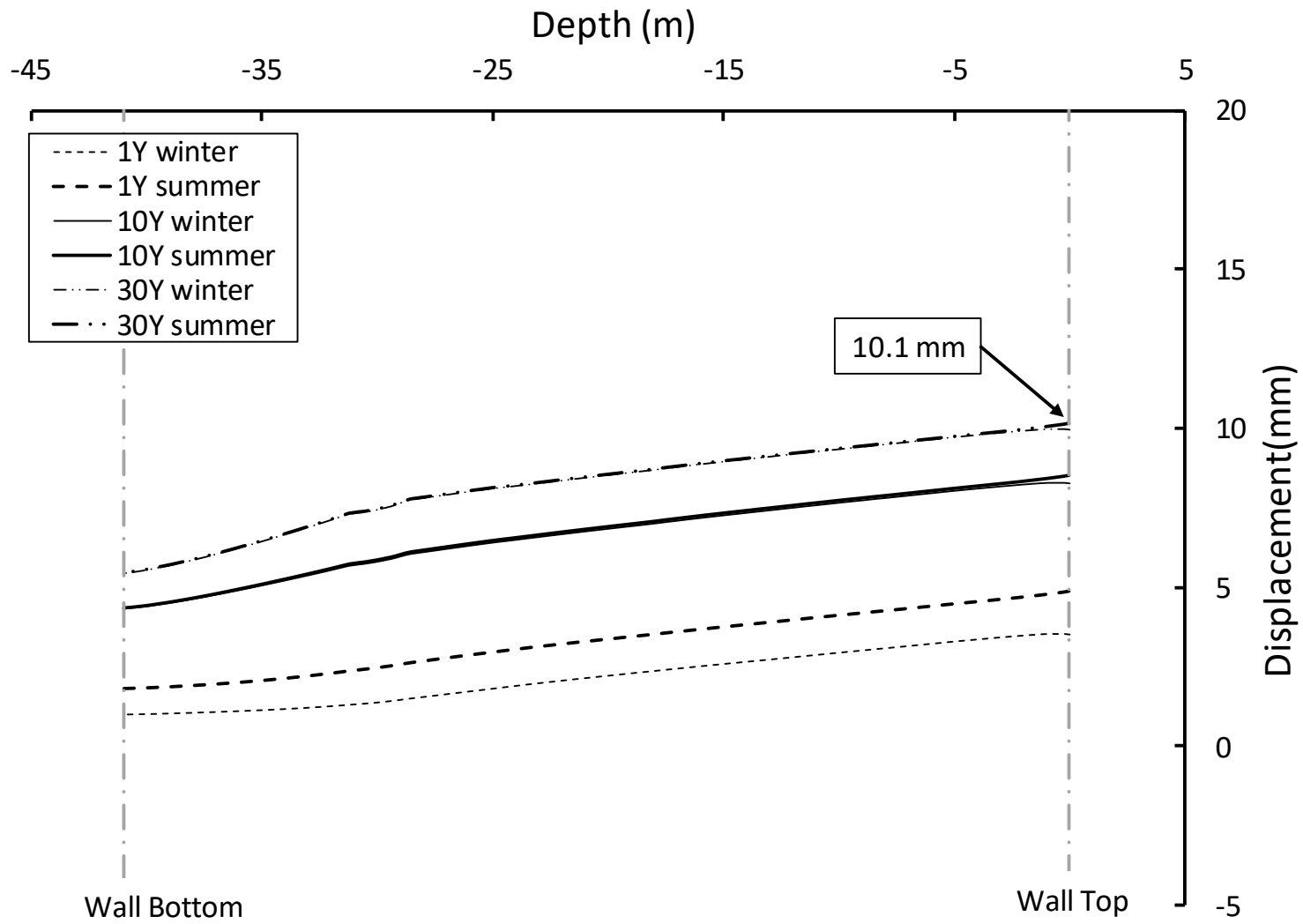


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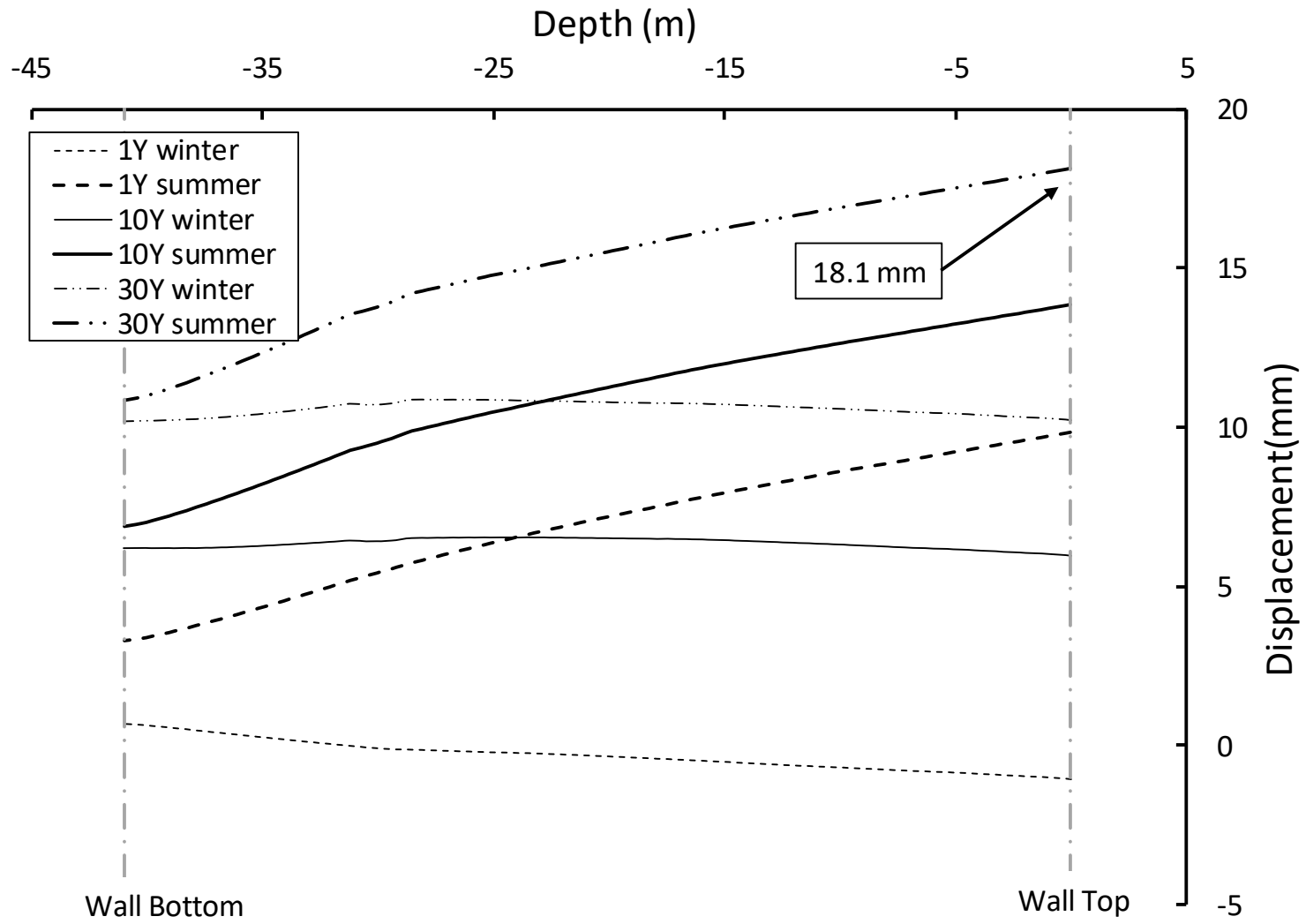


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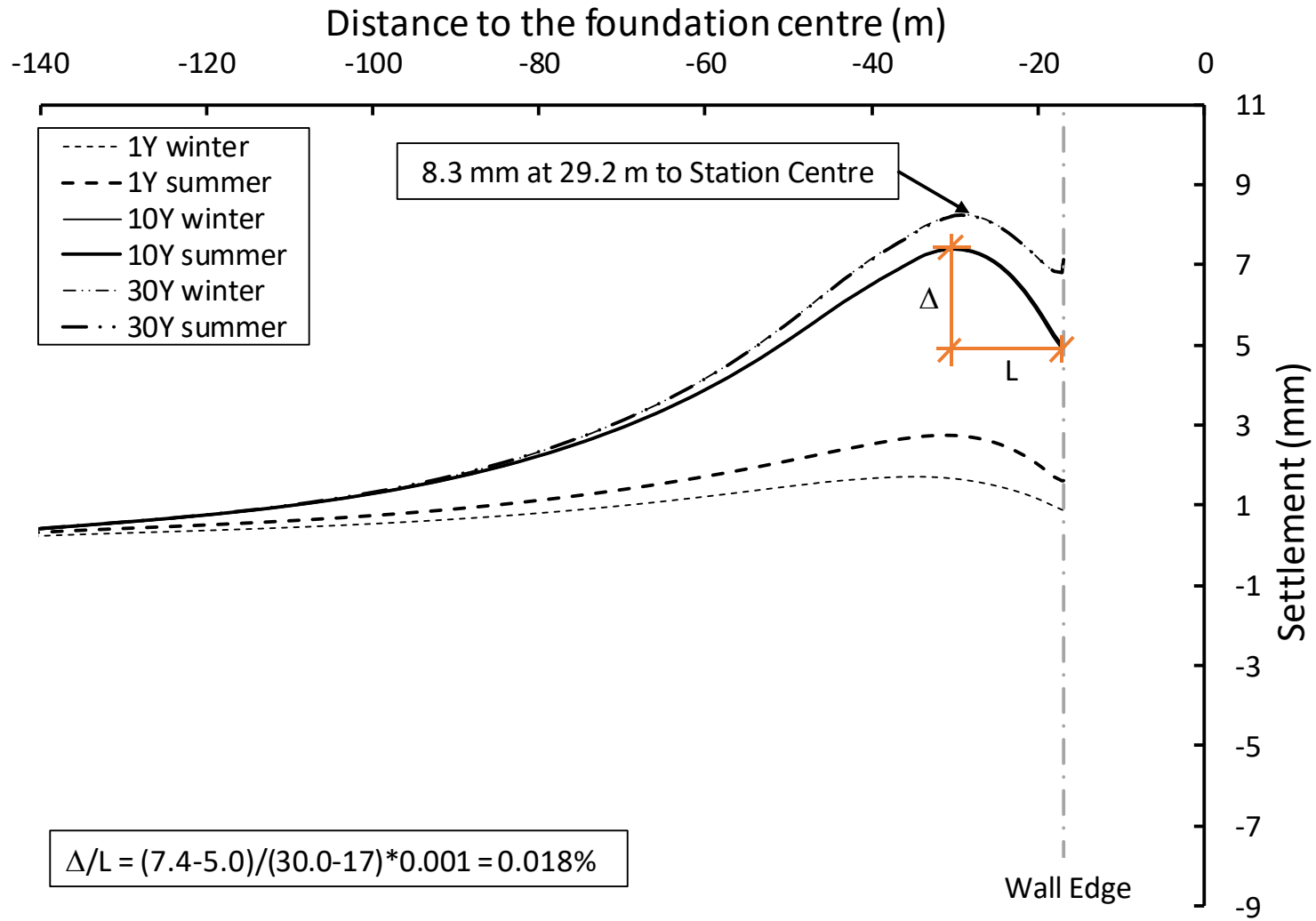


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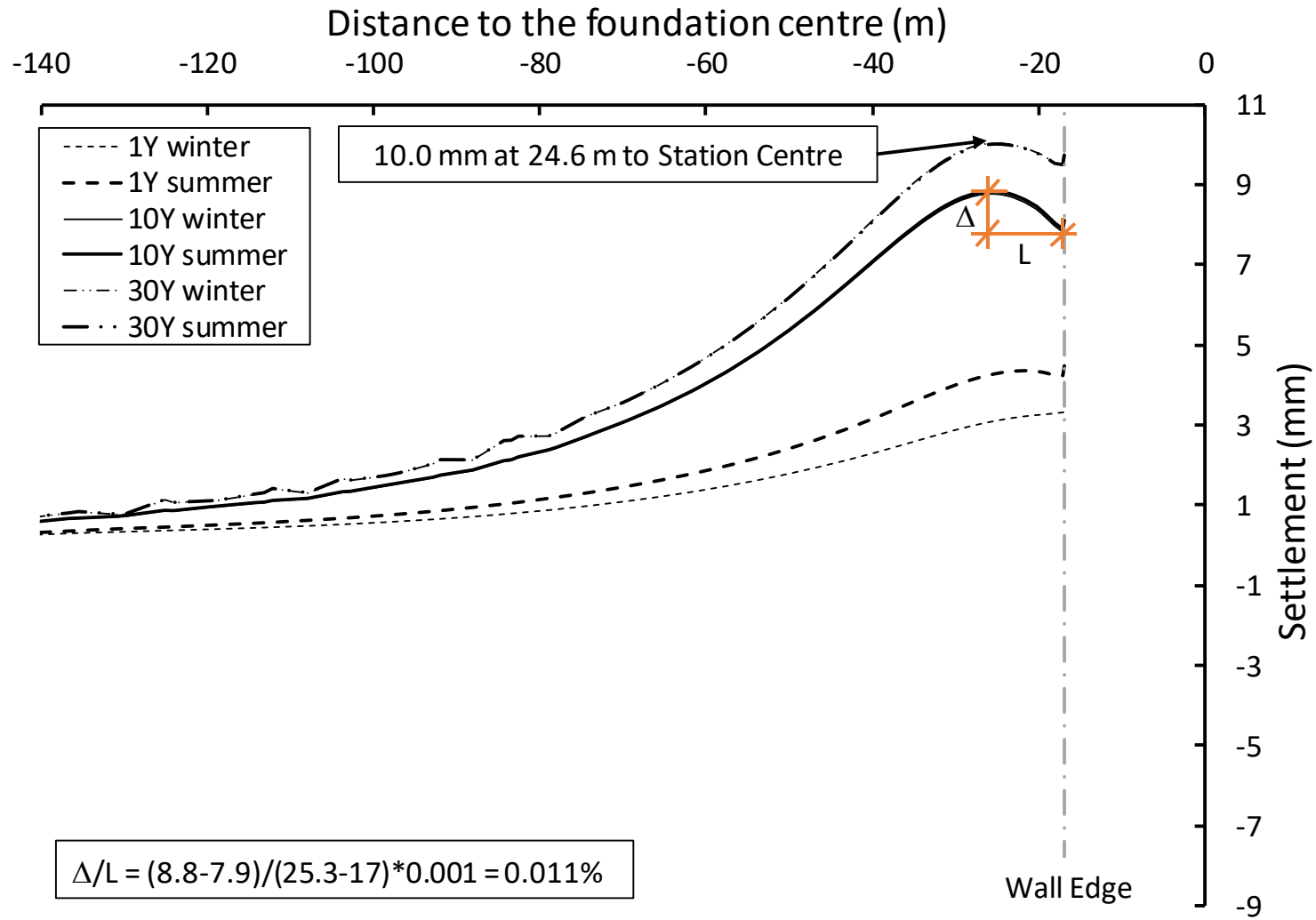


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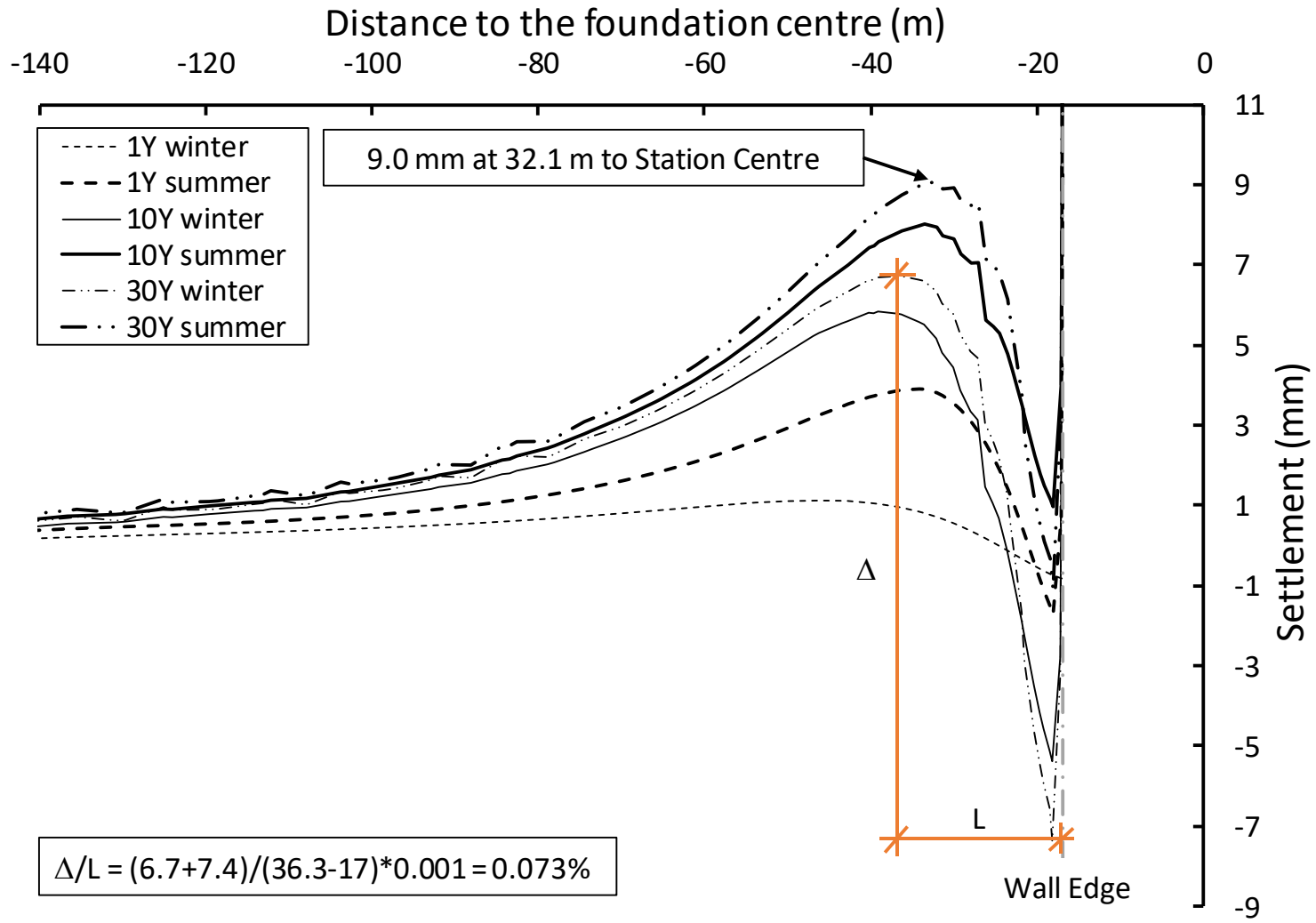


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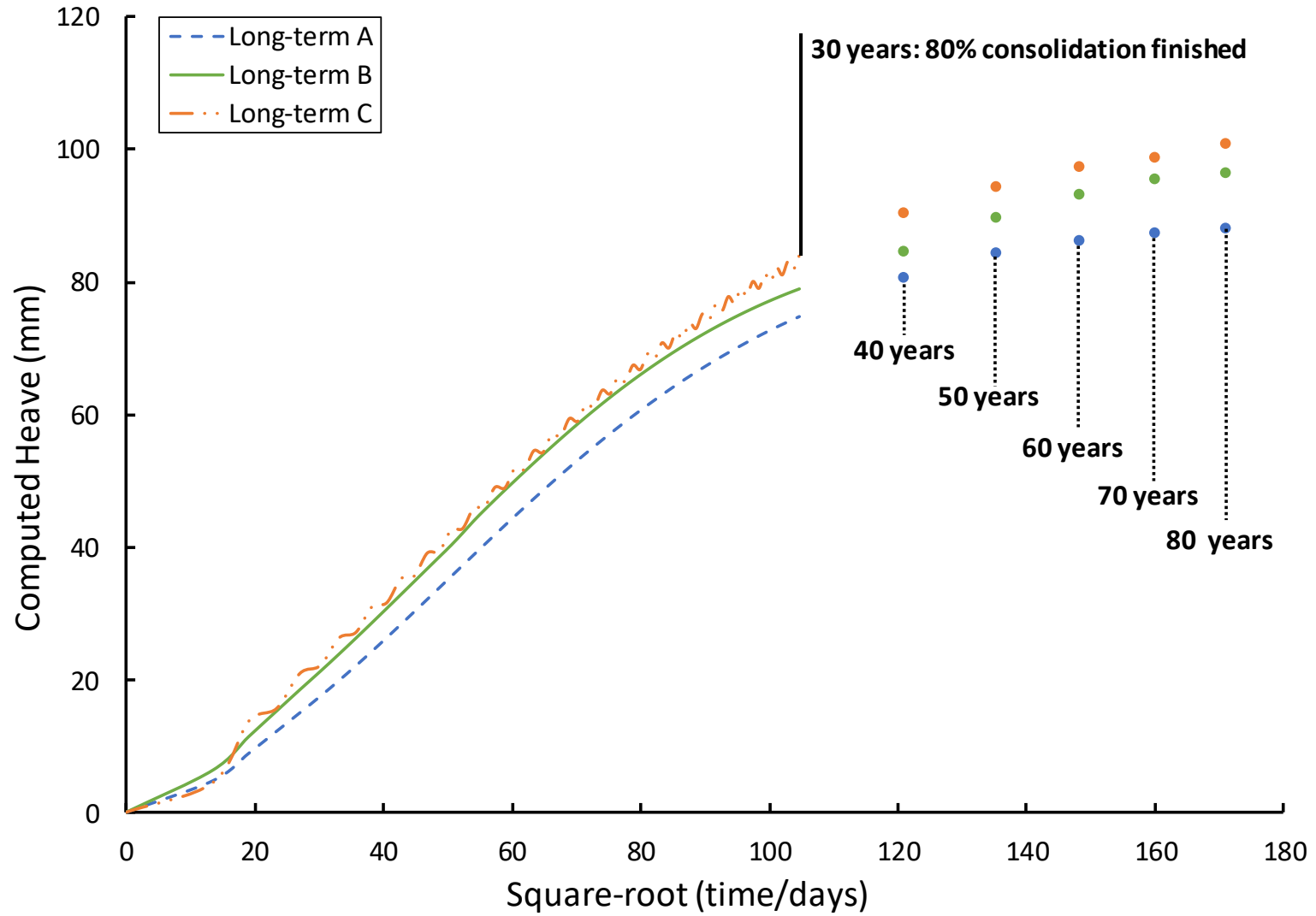




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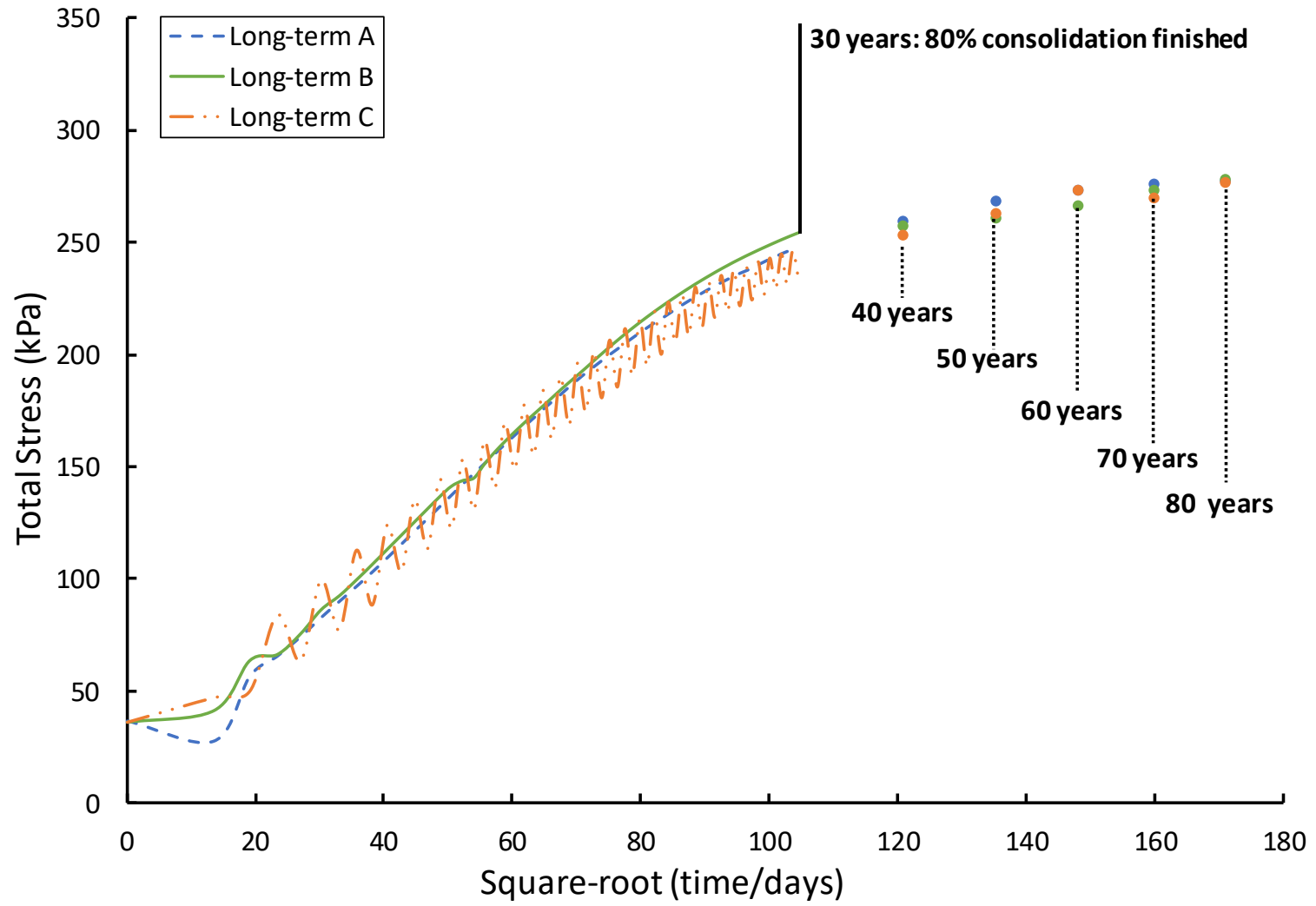


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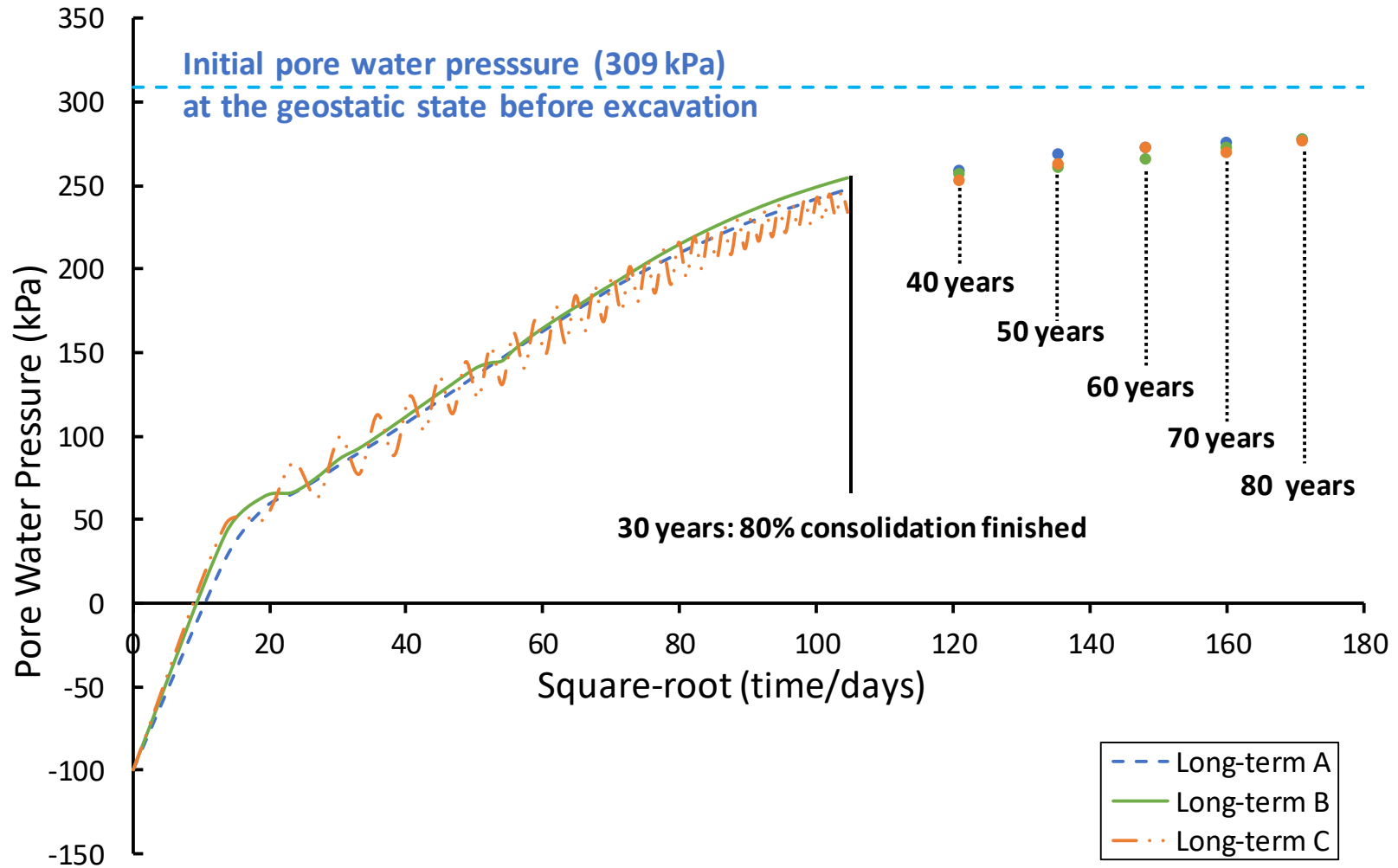


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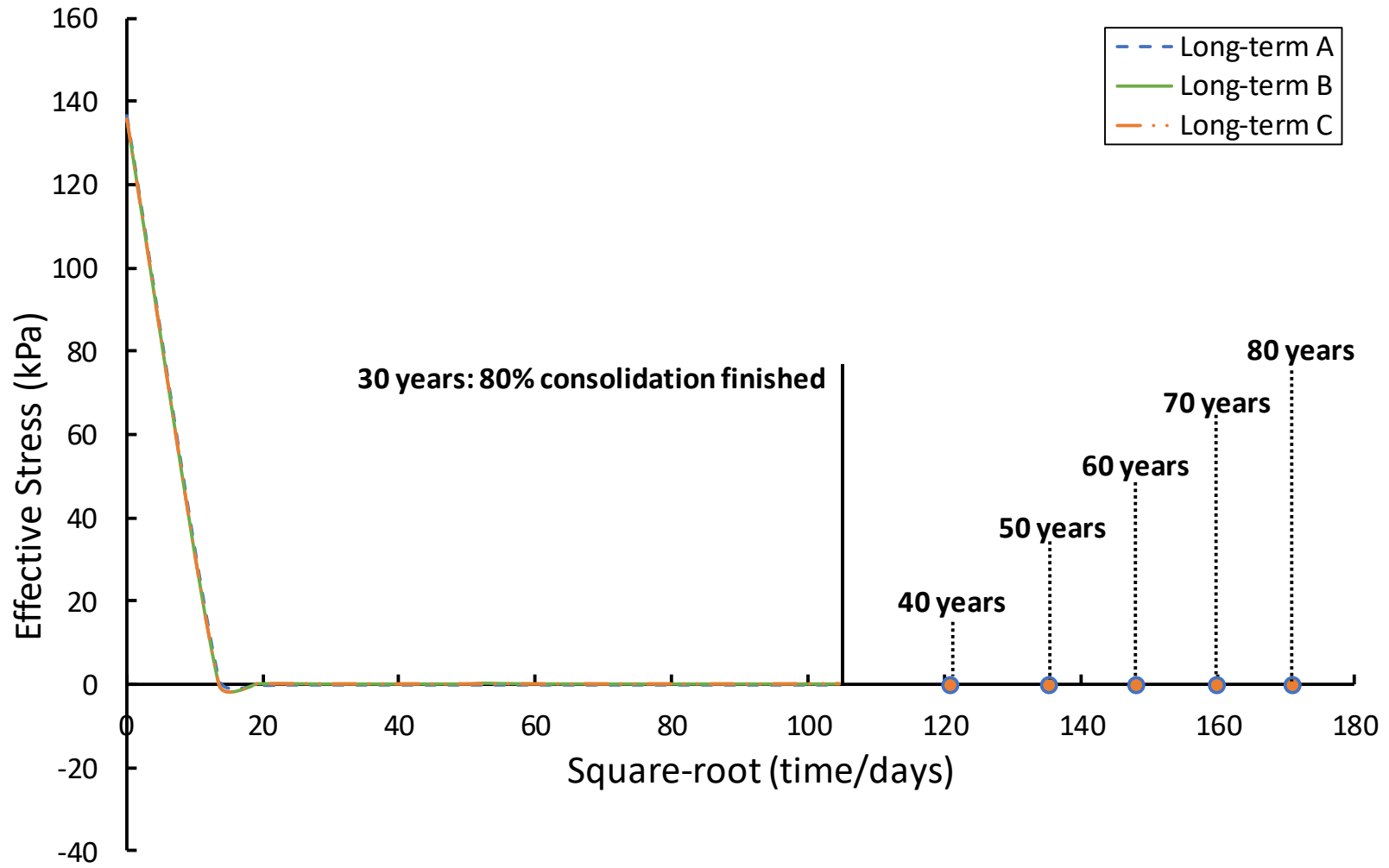


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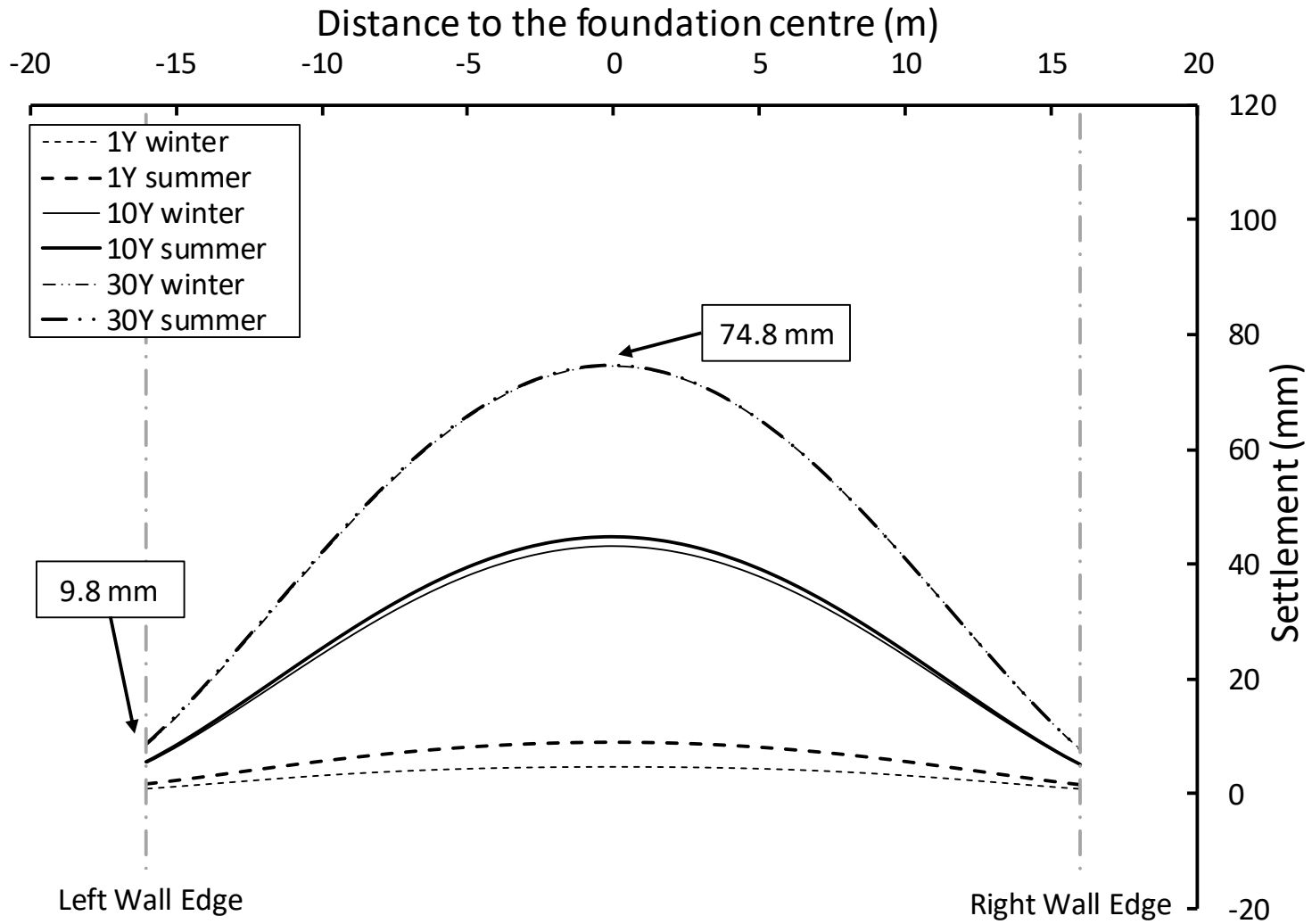


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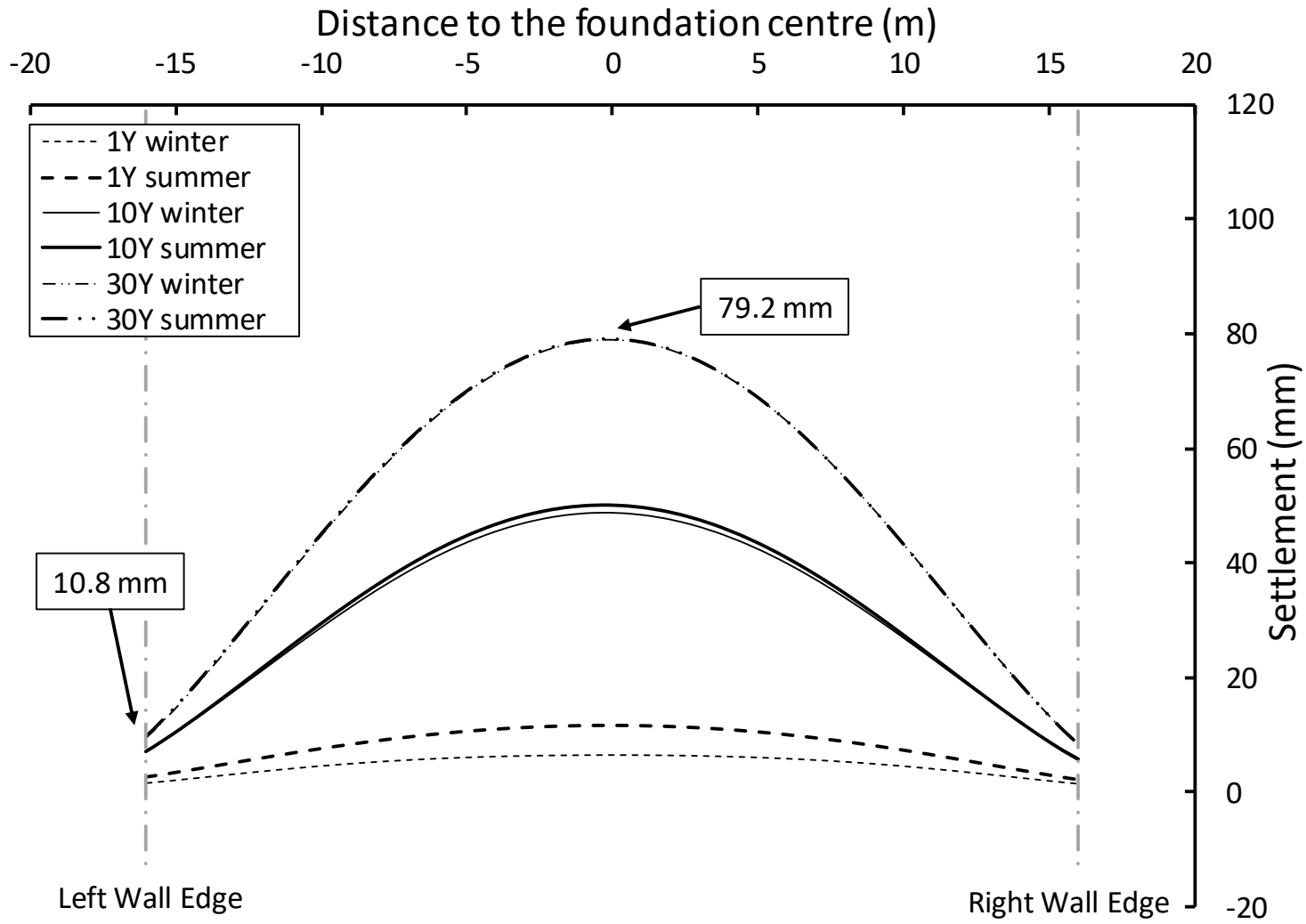


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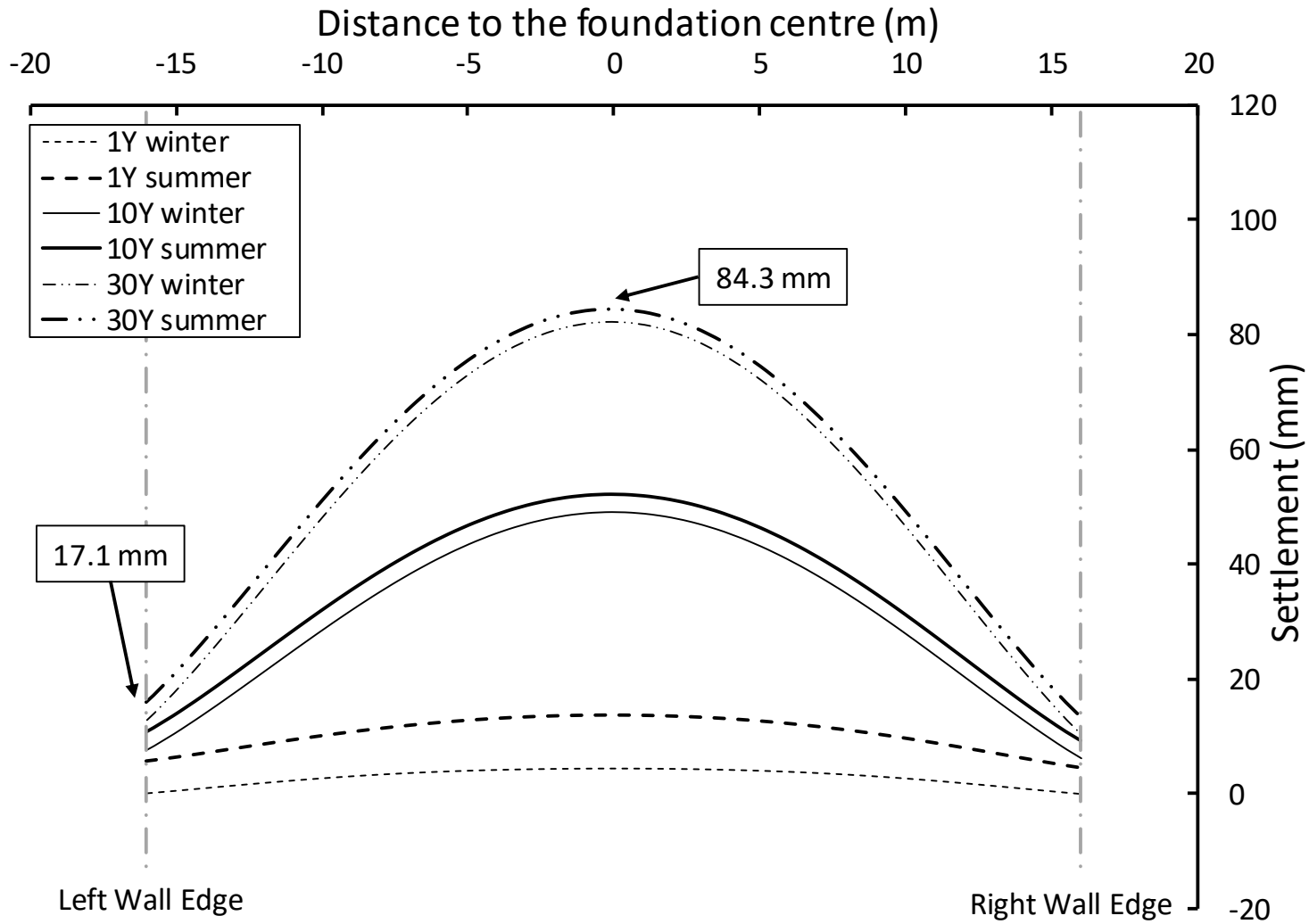


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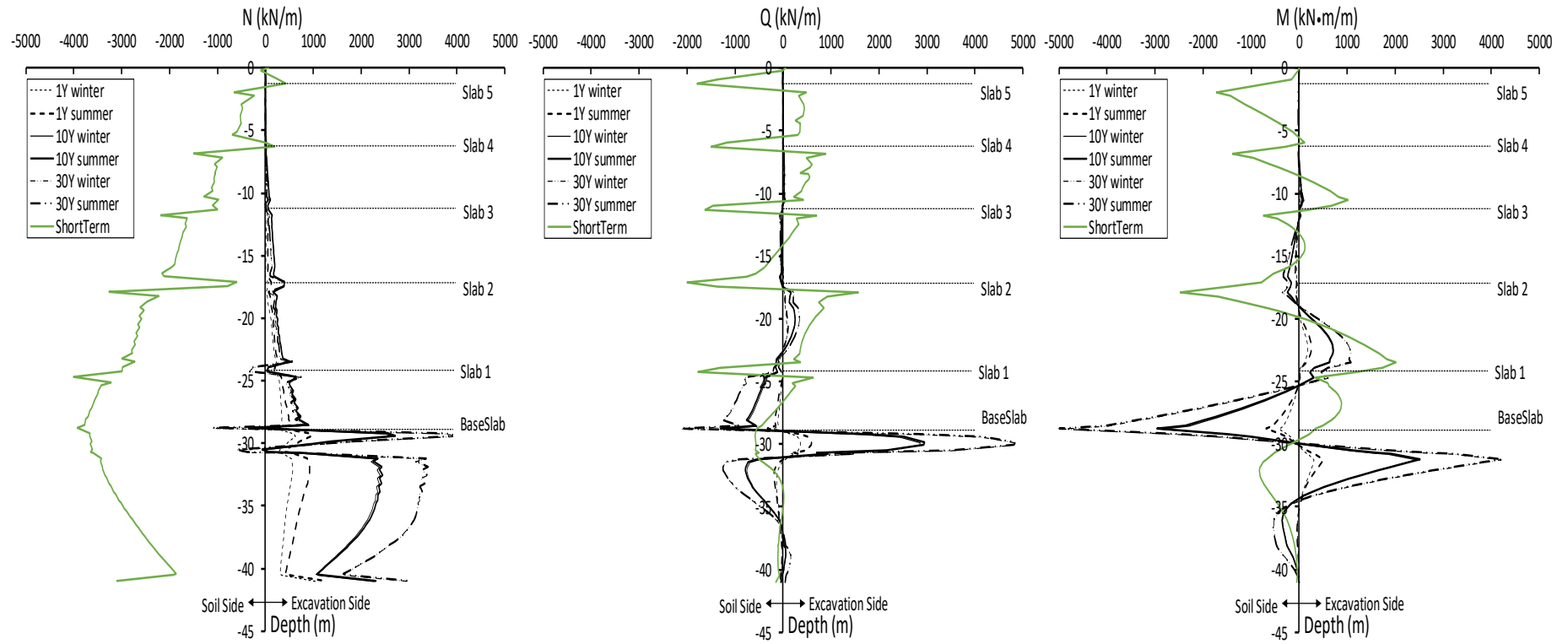


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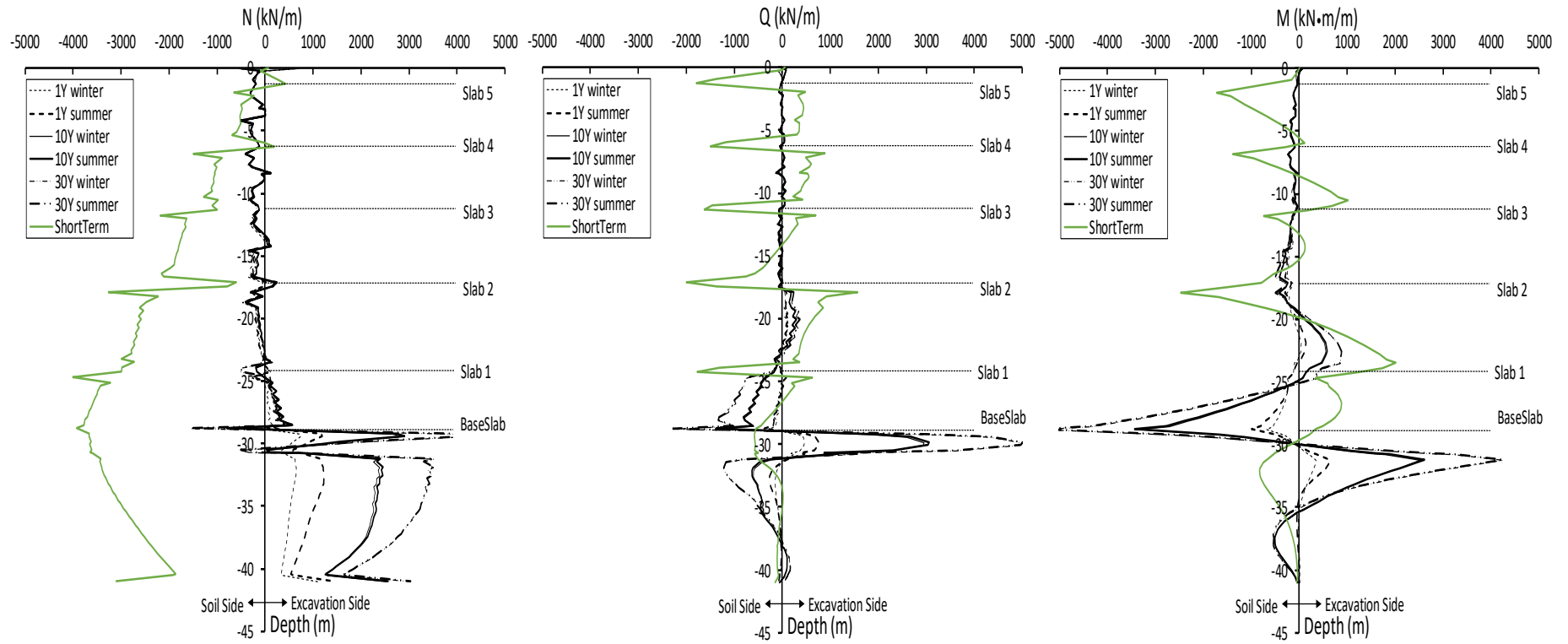




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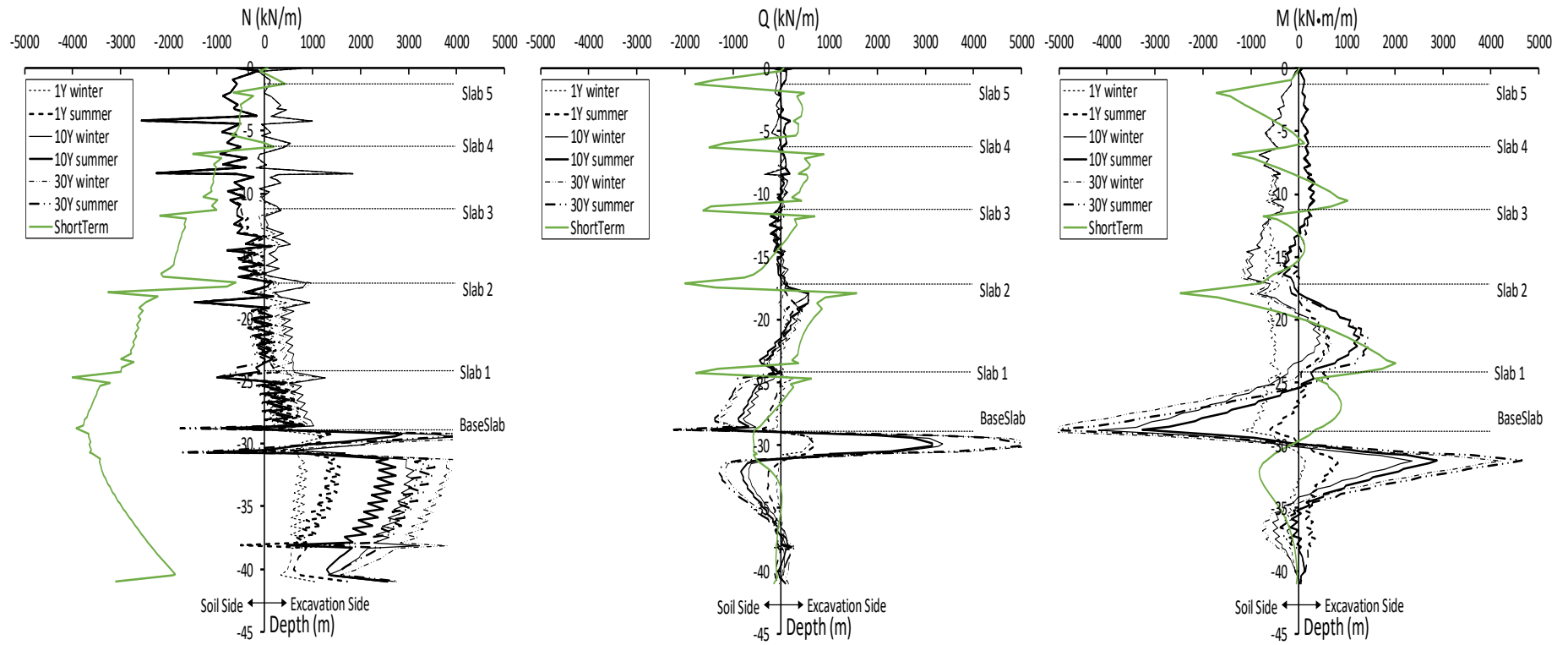


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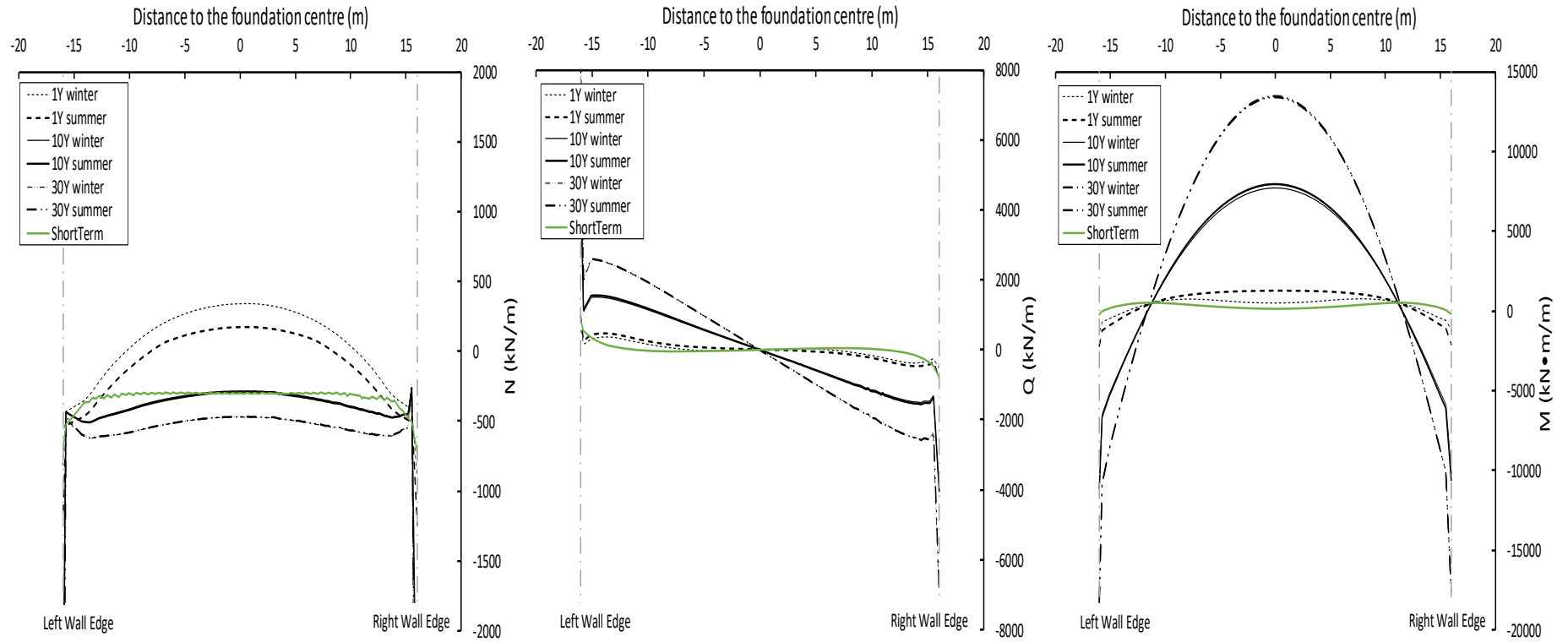


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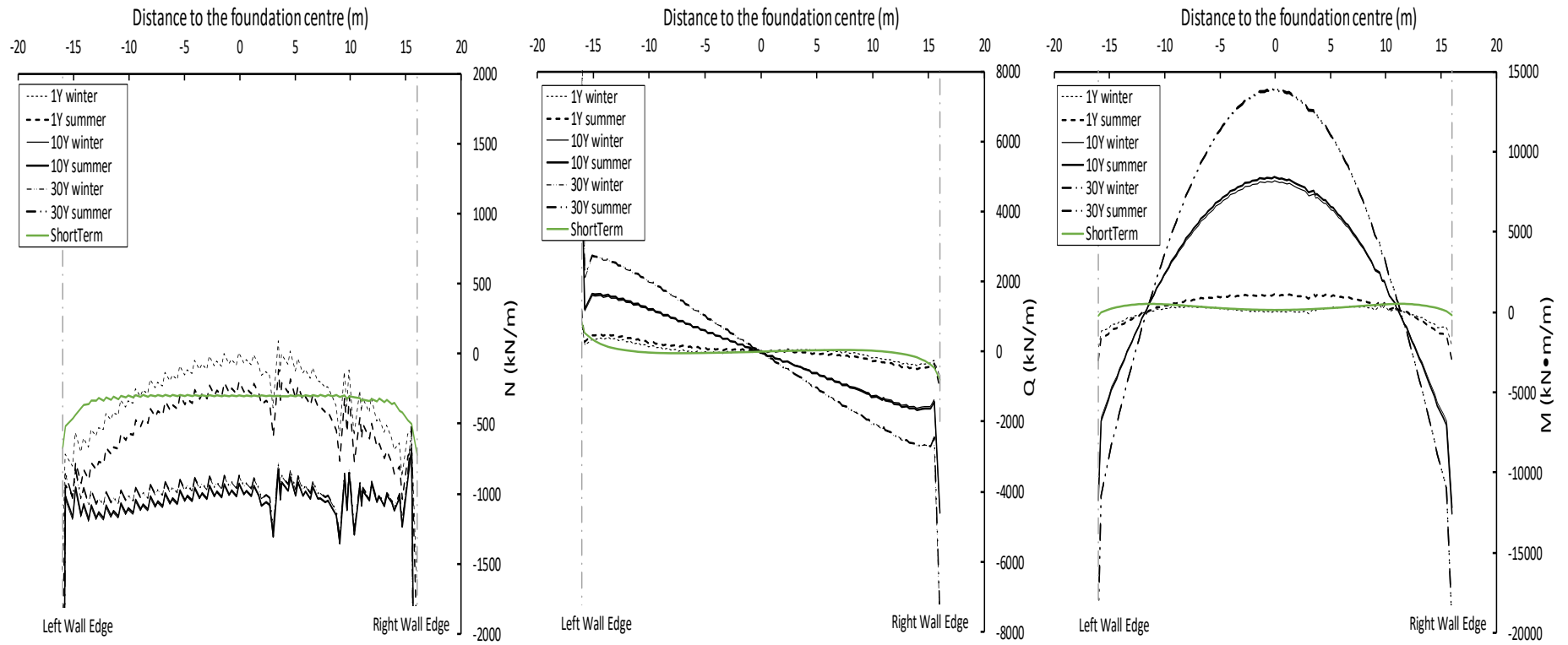


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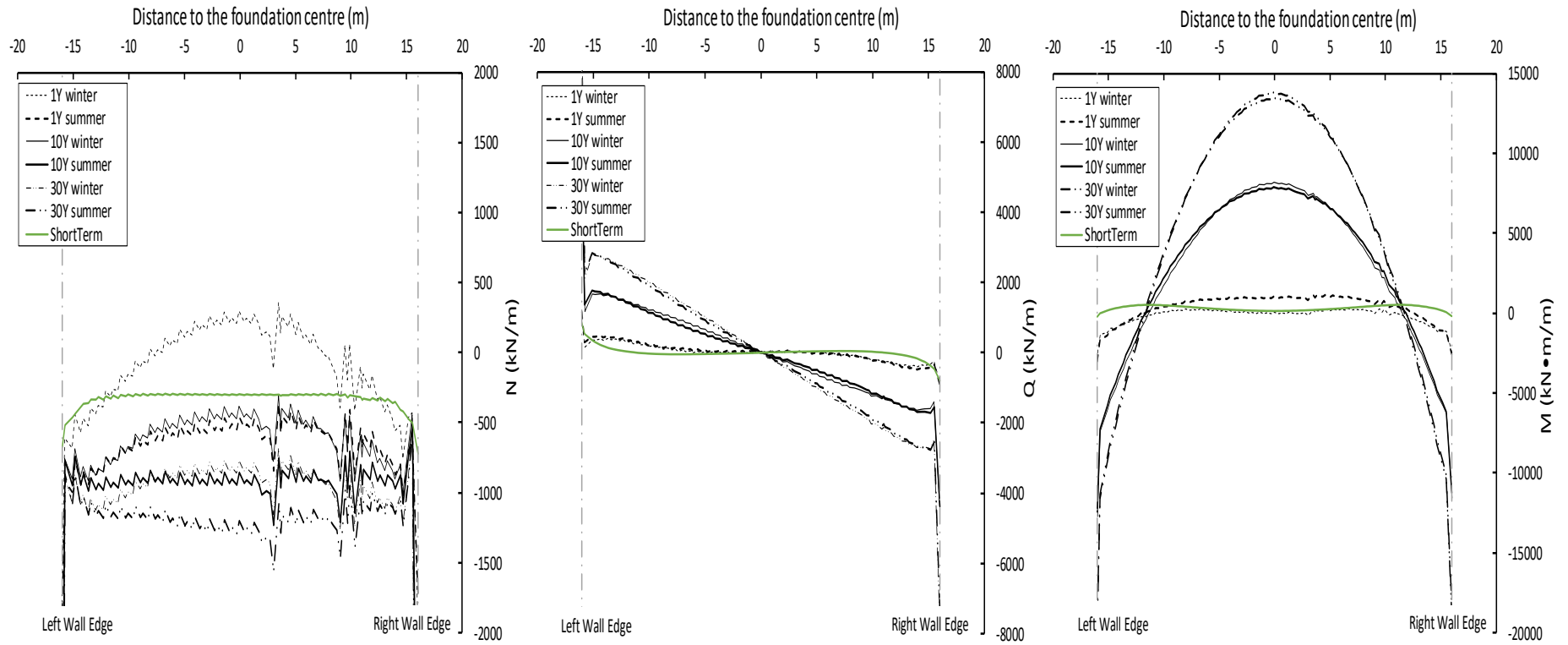


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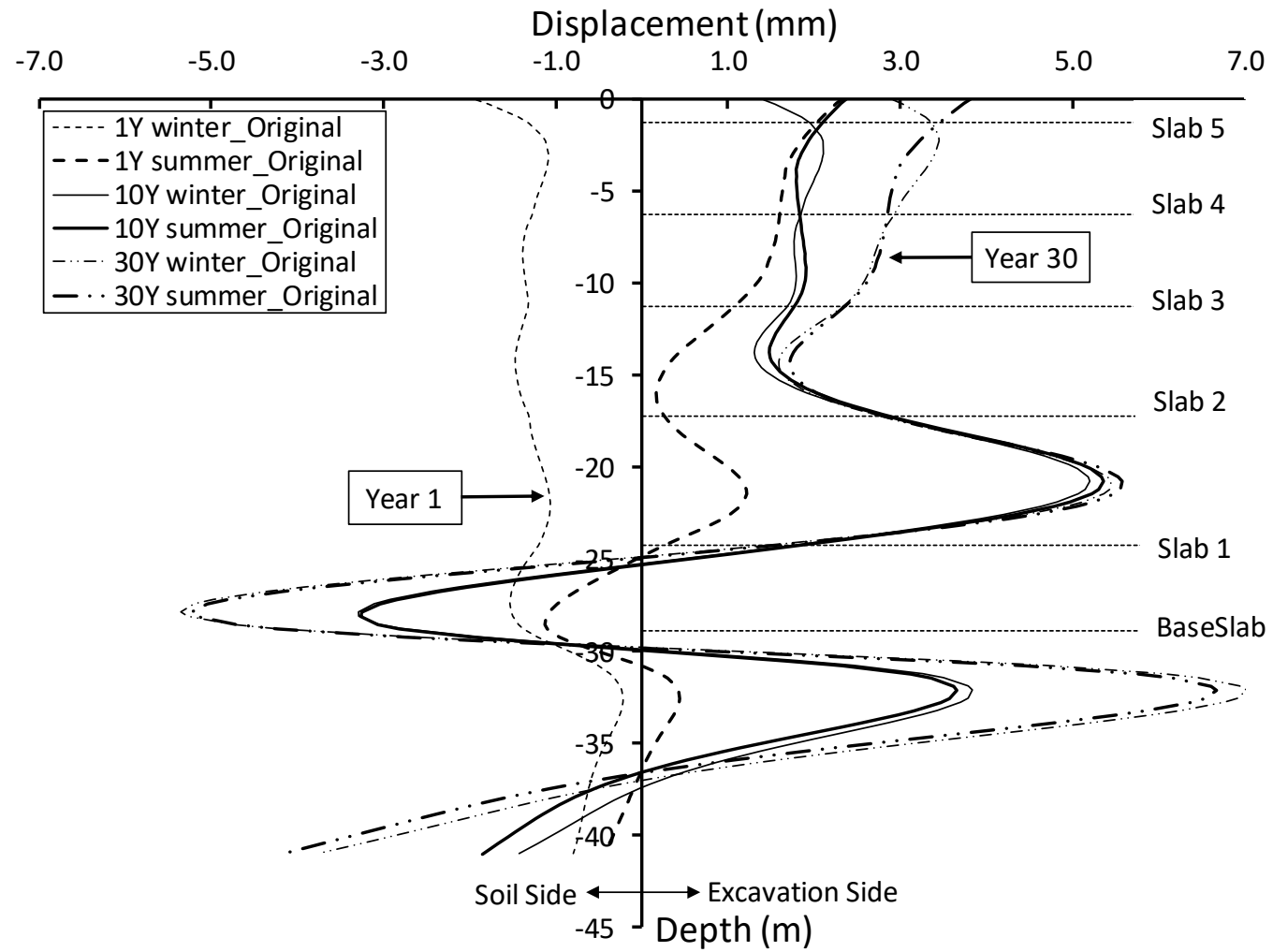


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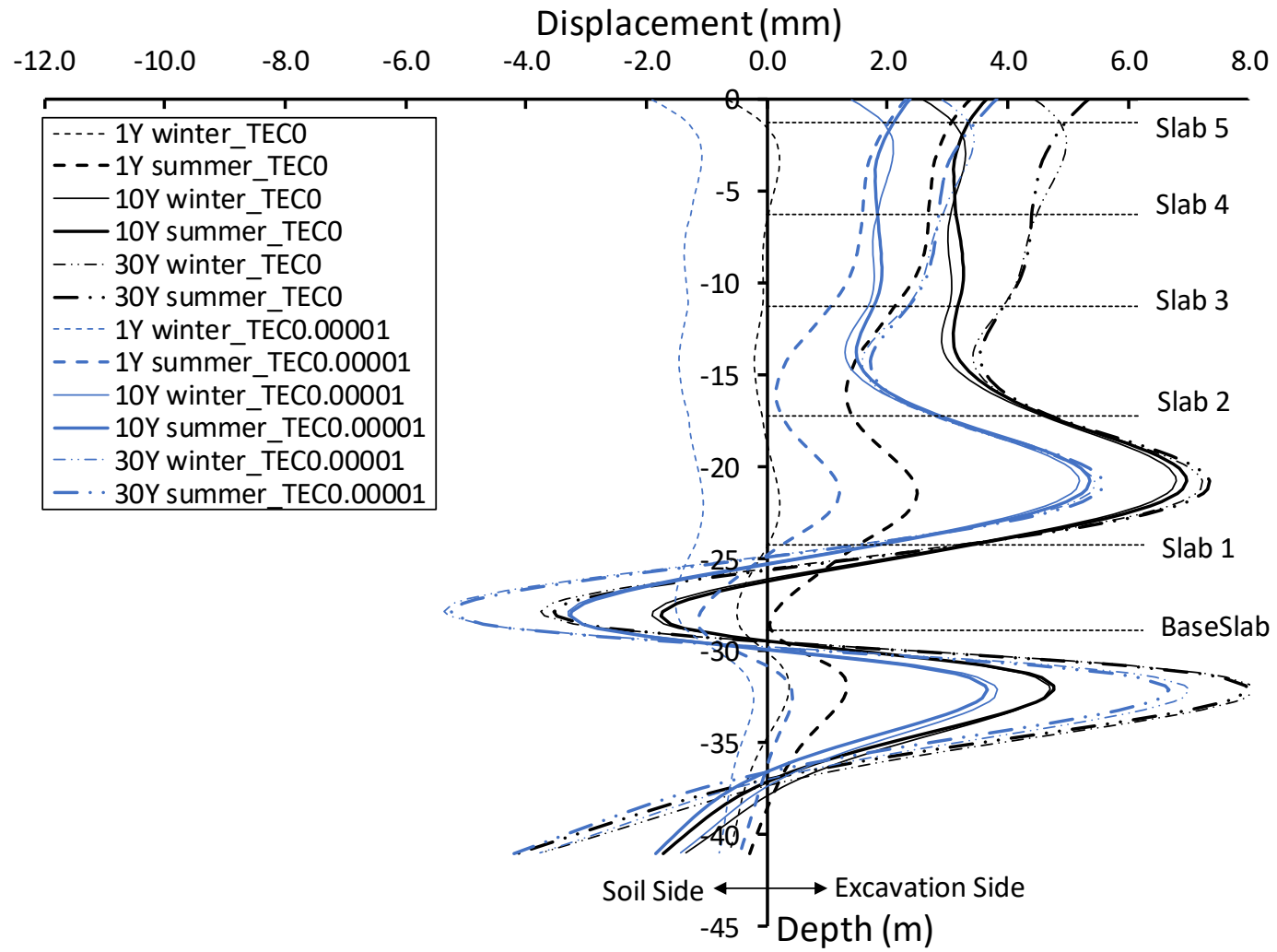


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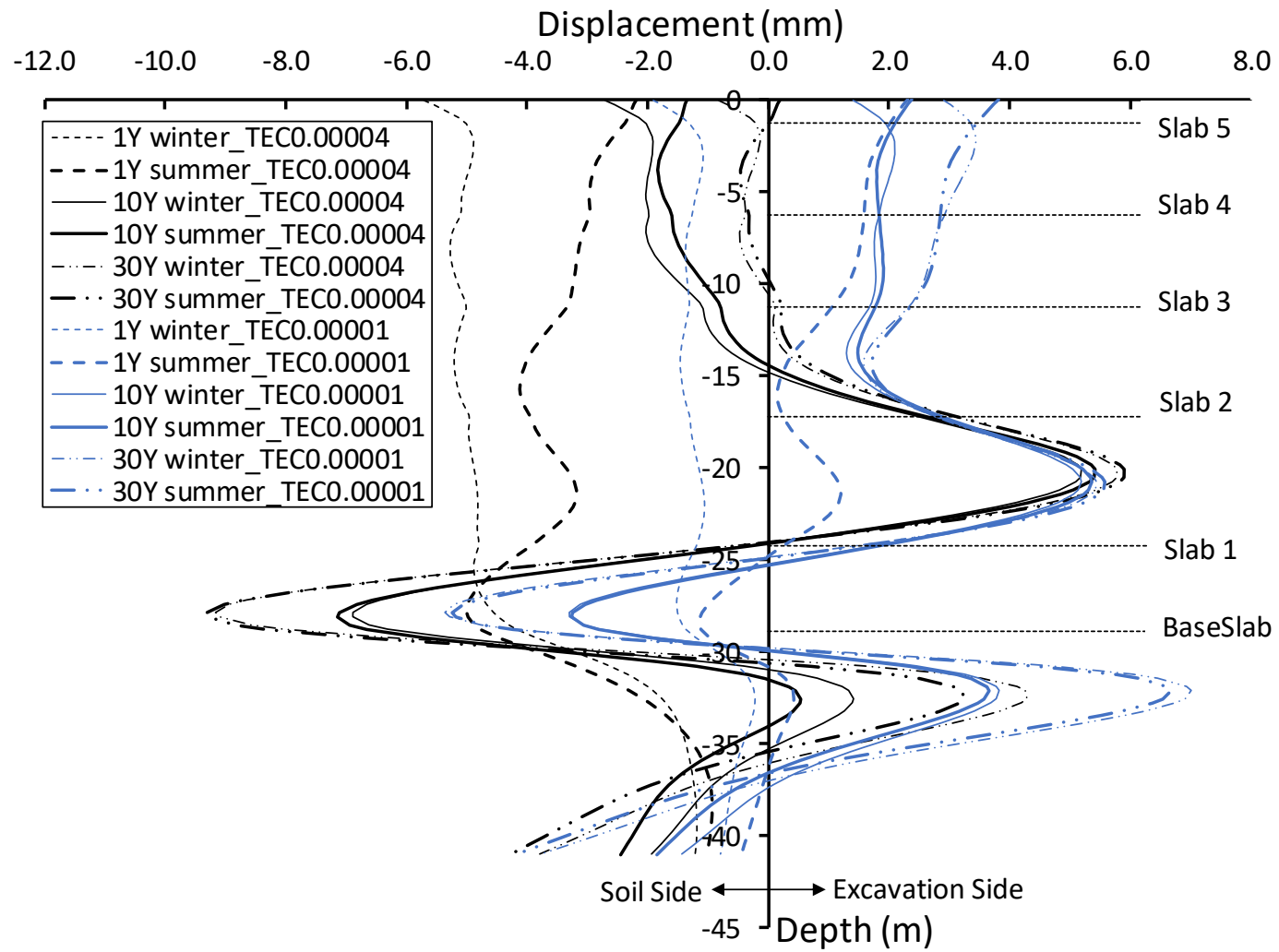


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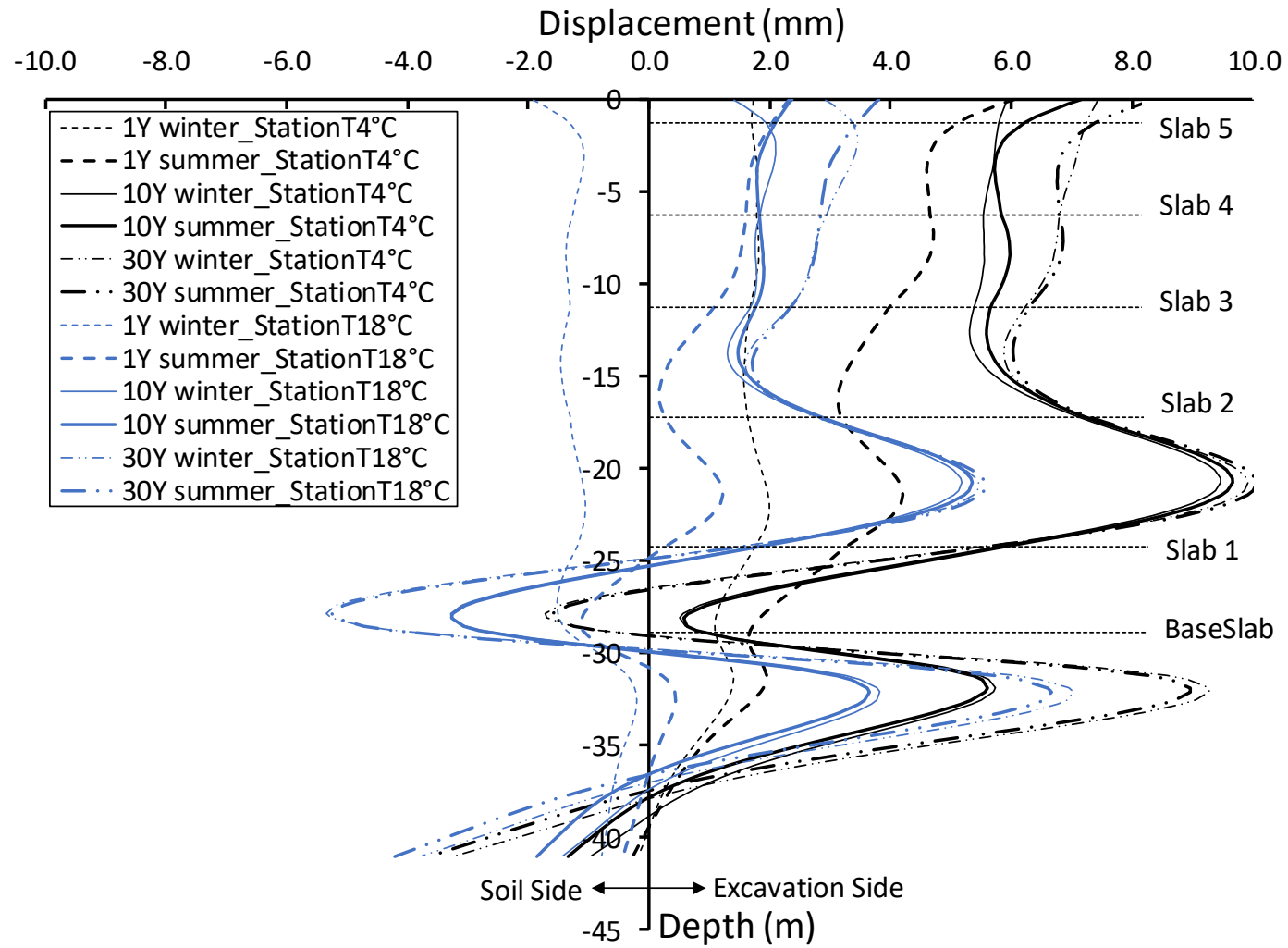




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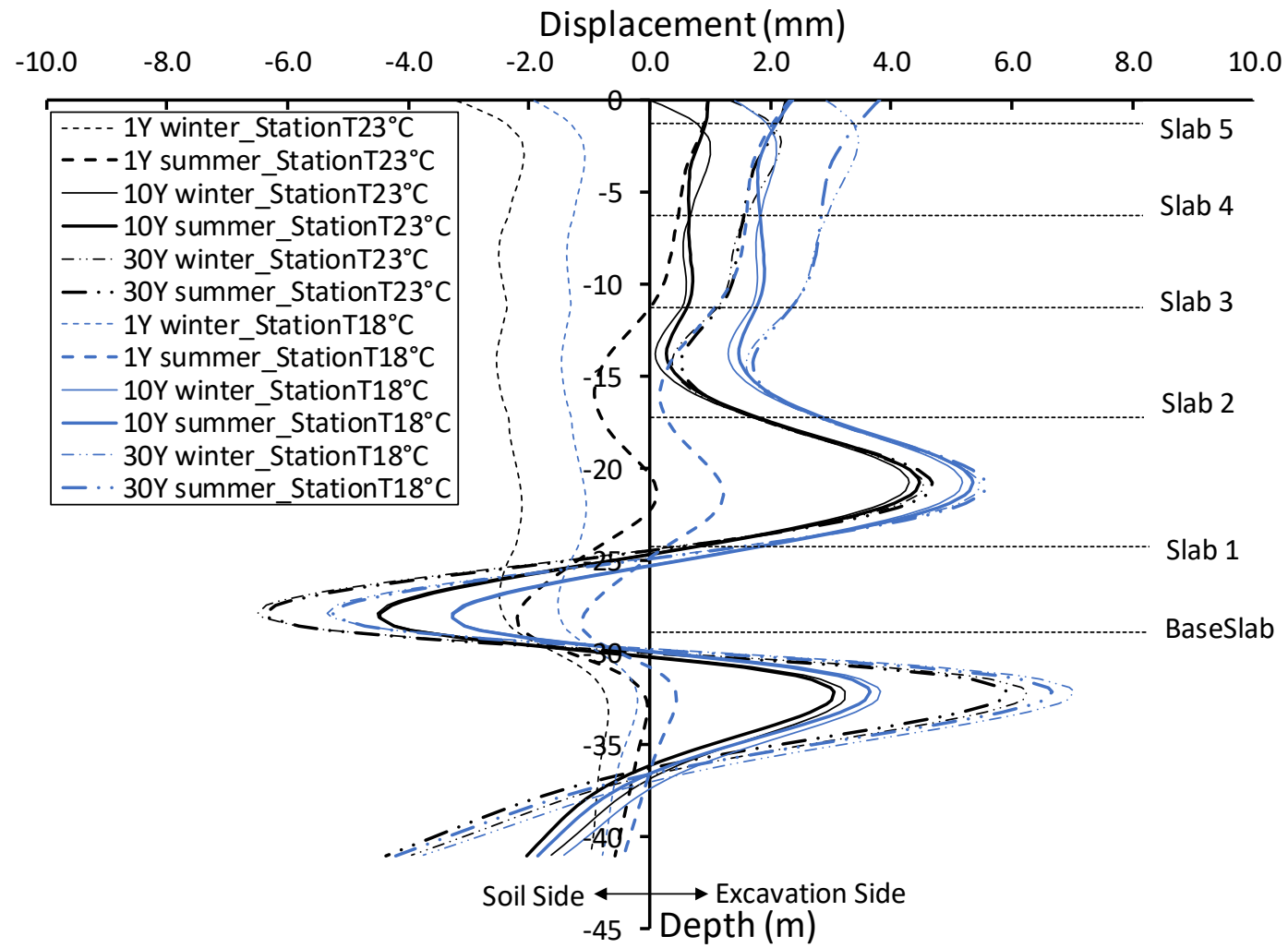


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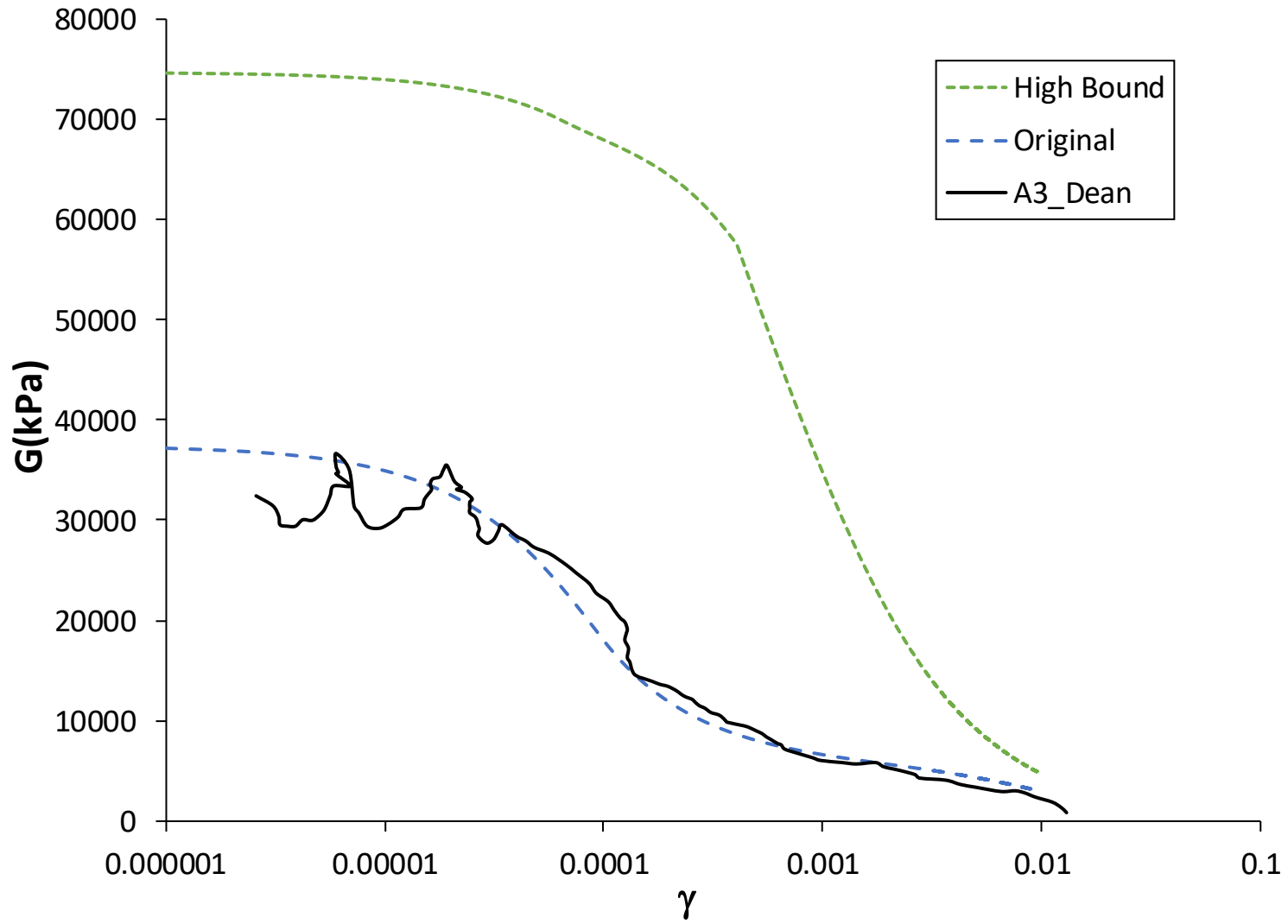


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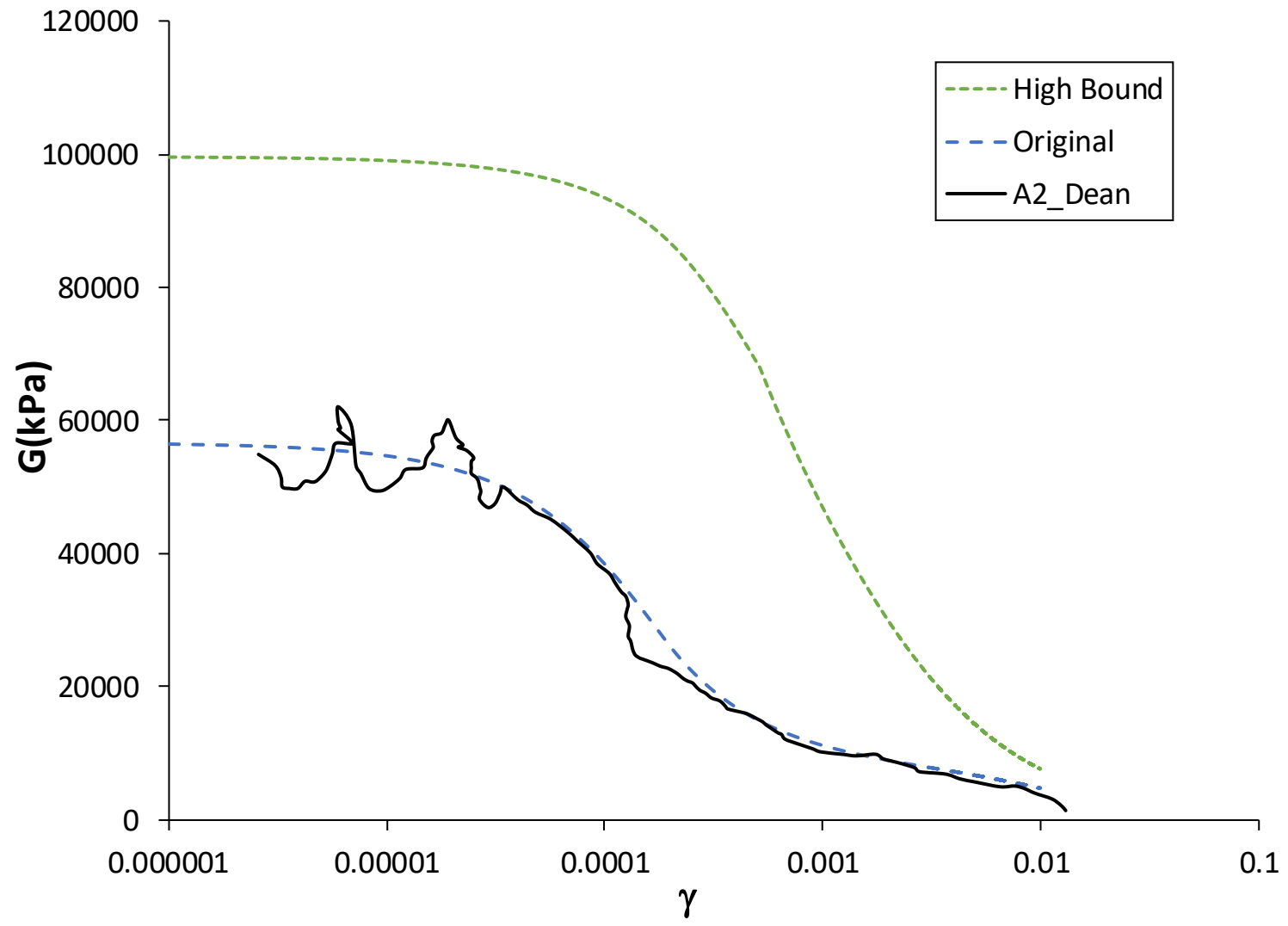


Figure 22c

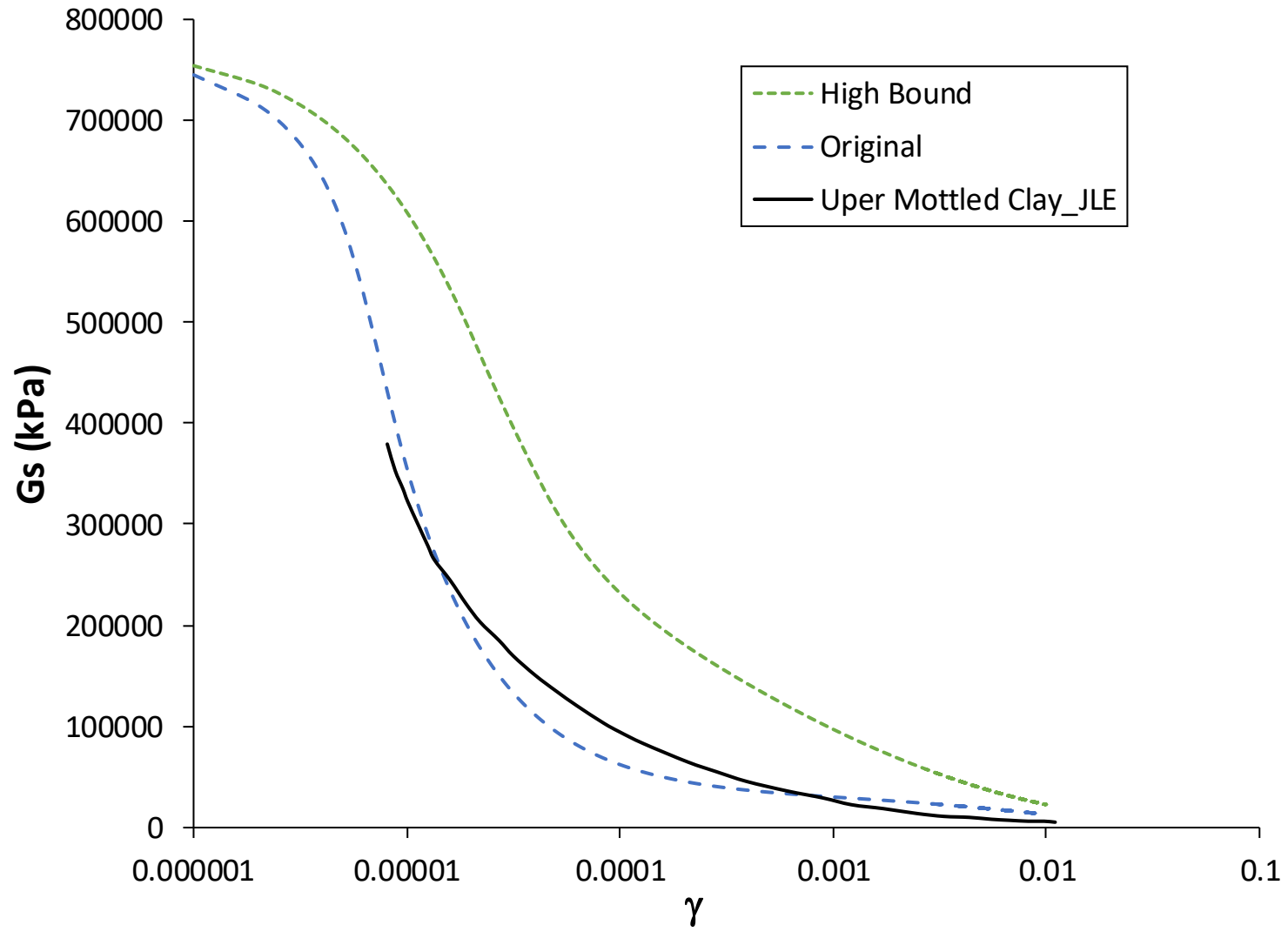


Figure 22d

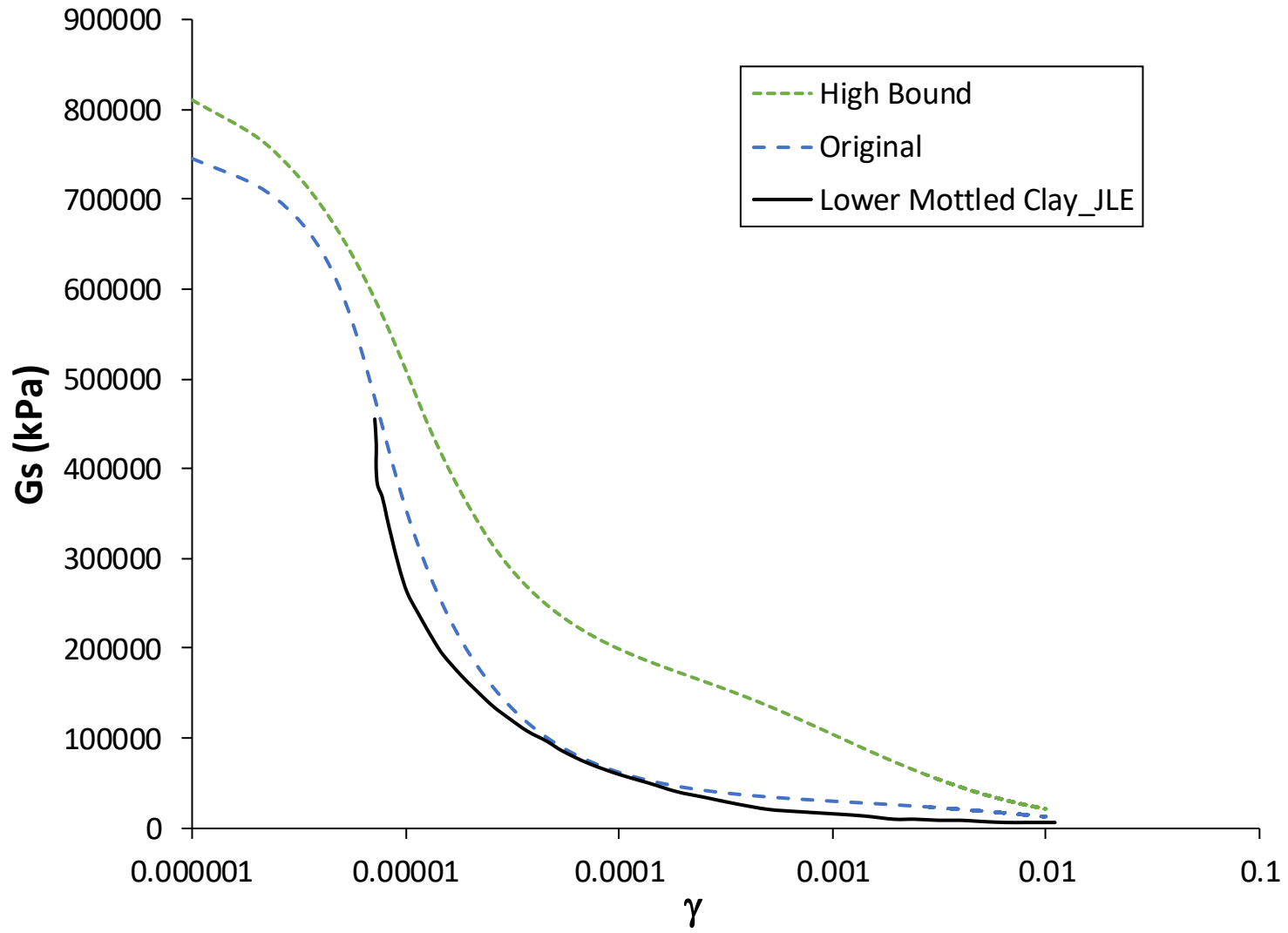


Figure 23a&b

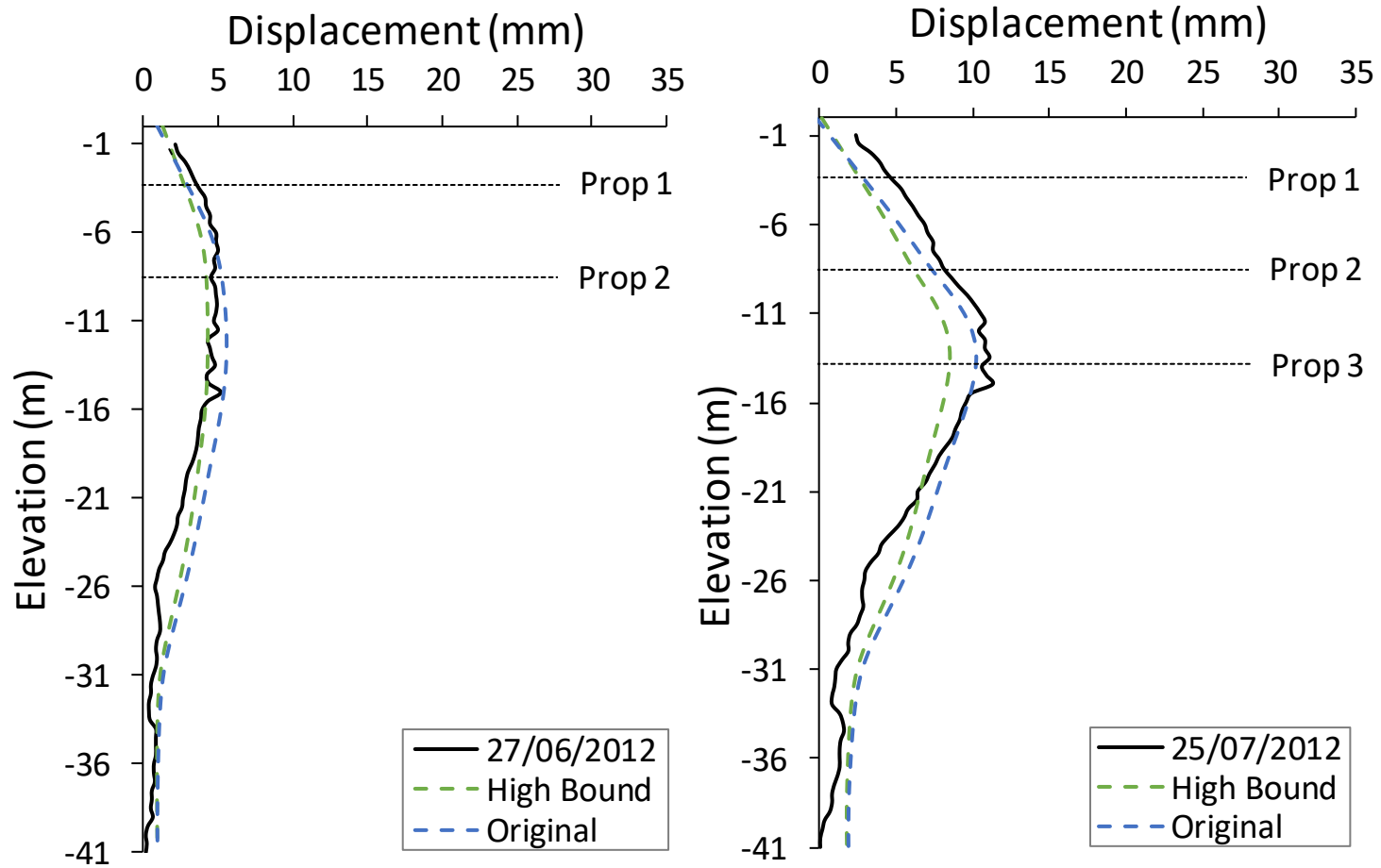


Figure 23c&d

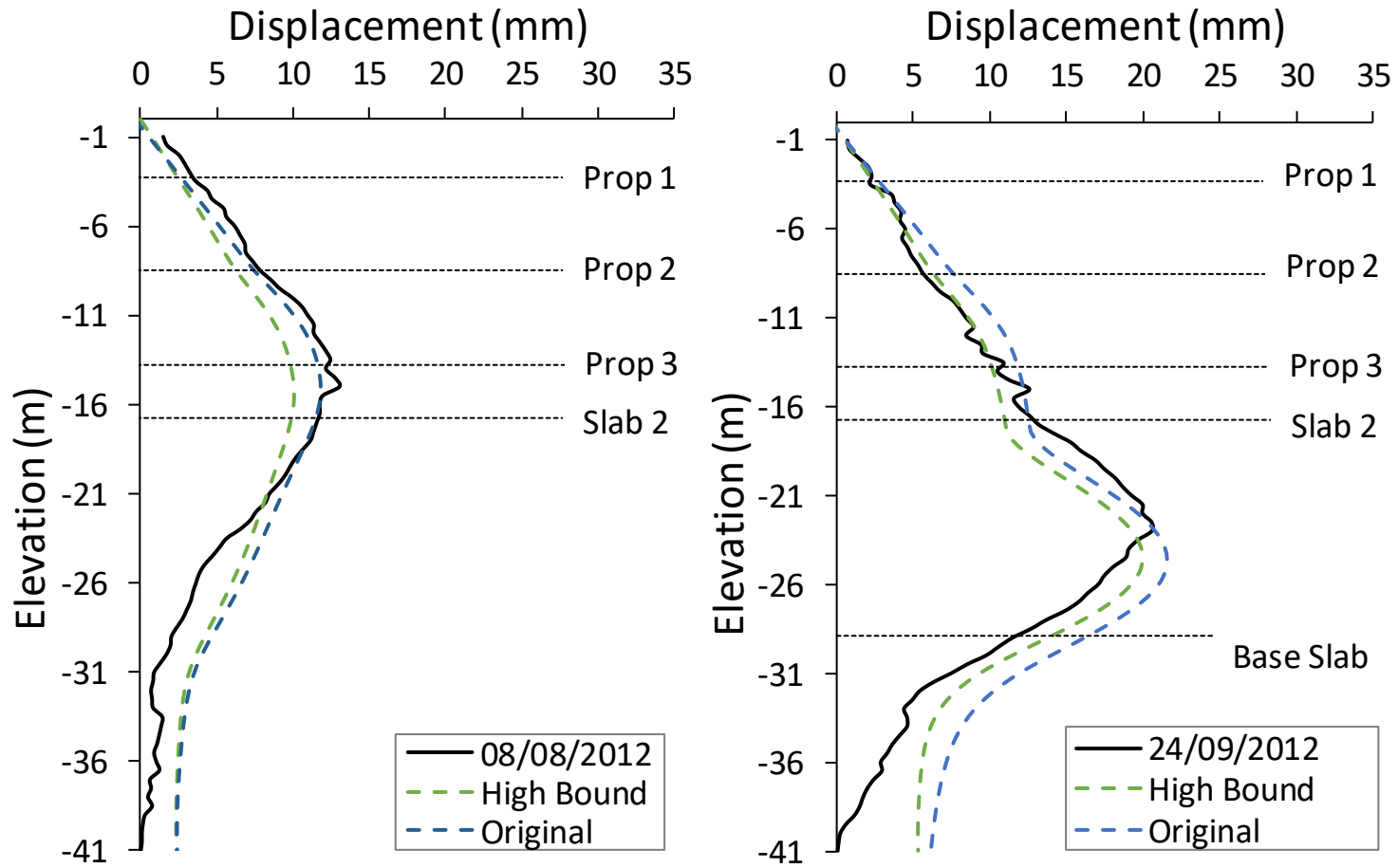


Figure 24

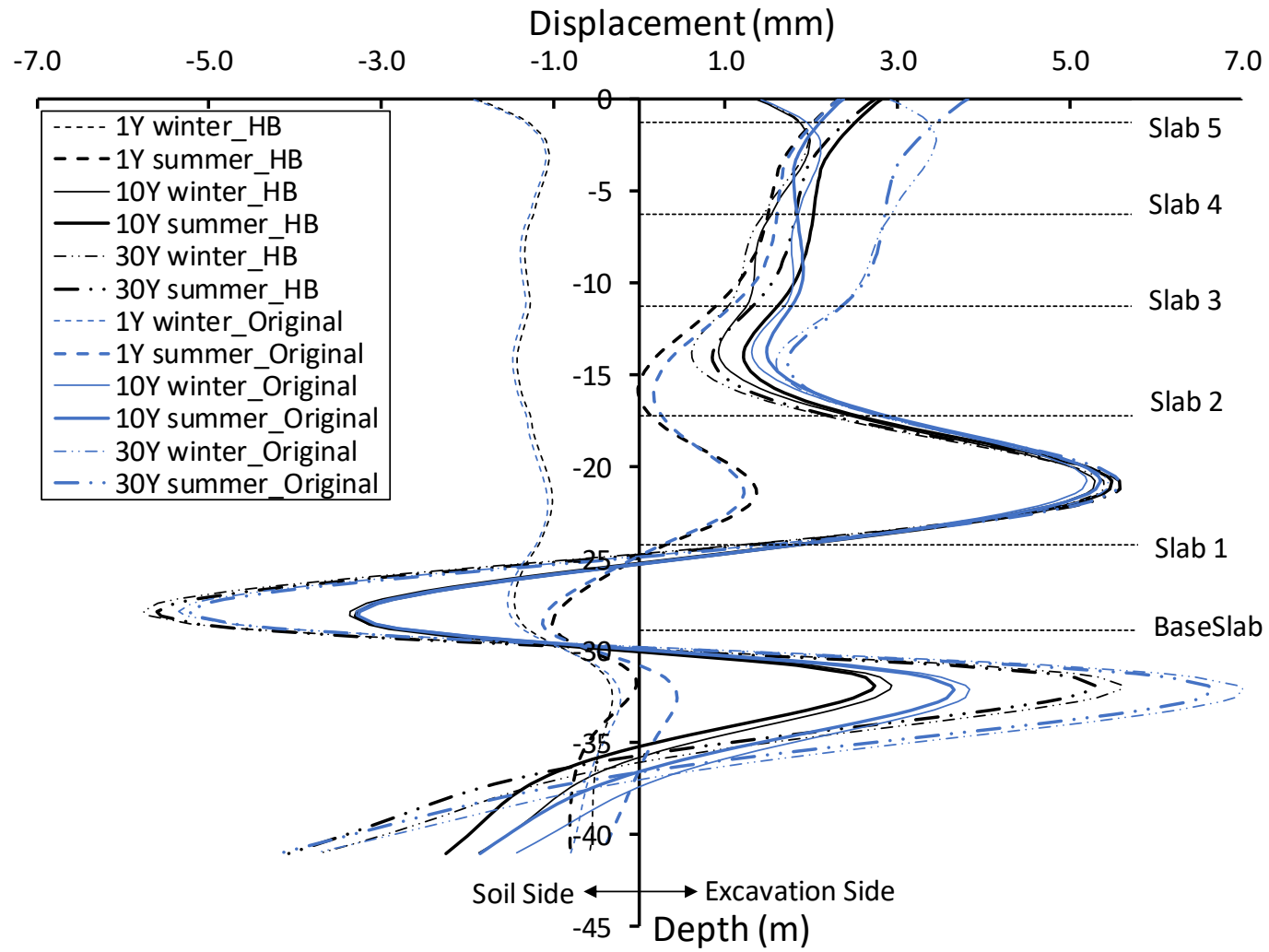




Table 1 – Prop (steel) properties (Zdravkovic et al., 2005)

Material type	E, kPa	D <sub>e</sub> , m	Thickness, mm	EA, kN	Spacing, m
Elastic	$2.05 \times 10^8$	1.0	16	$1 \times 10^8$	2

Table 2 – Wall and slab properties (Gaba et al., 2003)

Material set	$\gamma$ , kN/m <sup>3</sup>	E, kPa	$\nu$	C <sub>s</sub> , kJ/t/K	$\lambda_s$ , kW/m/K	$\rho_s$ , t/m <sup>3</sup>	$\alpha$ , 1/K	K <sub>0</sub>
Linear elastic, non-porous	24.0	$2.59 \times 10^7$	0.2	920.0	$1.75 \times 10^{-3}$	2.50	$1 \times 10^{-5}$	1.0

Table 3 – Mechanical properties of soil layers (Hight et al., 2004, Rui, 2014)

Soil Description	E, kPa	Material set	$\nu$	c, kPa	$\phi$ , °	$\psi$ , °
Made Ground	9600	MC, drained, saturated	0.2	0	25	0
Terrace Ground	48000	MC, drained, saturated	0.2	0	35	0
London Clay A3	see Table 5	HSS, undrained A, saturated	0.2	5	25	0
London Clay A2	see Table 5	HSS, undrained A, saturated	0.2	5	25	0
Lambeth Group UMC	see Table 5	HSS, undrained A, saturated	0.2	230	28	0
Lambeth Group LMC	see Table 5	HSS, undrained A, saturated	0.2	230	28	0
Thanet Sand	400800	MC, drained, saturated	0.2	0	27	0
Chalk	400800	MC, drained, saturated	0.2	0	32	0

Table 4 – Thermal properties of soil layers (Rui, 2014)

Soil description	$\gamma$ , kN/m <sup>3</sup>	$k$ , m/day	$C_s$ , kJ/t/K	$\lambda_s$ , kW/m/K	$\rho_s$ , t/m <sup>3</sup>	$\alpha$ , 1/K	$k_0$
Made Ground	20	8.64	1400	$1.25 \times 10^{-3}$	2.0	$1.0 \times 10^{-5}$	0.6
Terrace Ground	21	8.64	1333	$1.80 \times 10^{-3}$	2.1	$1.0 \times 10^{-5}$	0.4
London Clay A3	20	$8.64 \times 10^{-6}$	1600	$1.60 \times 10^{-3}$	2.0	$1.0 \times 10^{-5}$	1.0
London Clay A2	21	$8.64 \times 10^{-6}$	1524	$1.60 \times 10^{-3}$	2.1	$1.0 \times 10^{-5}$	1.0
Lambeth Group UMC	21	$8.64 \times 10^{-6}$	1524	$2.10 \times 10^{-3}$	2.1	$1.0 \times 10^{-5}$	1.0
Lambeth Group LMC	21	$8.64 \times 10^{-6}$	1524	$2.10 \times 10^{-3}$	2.1	$1.0 \times 10^{-5}$	1.0
Thanet Sand	21	$8.64 \times 10^{-2}$	1333	$1.27 \times 10^{-3}$	2.1	$1.0 \times 10^{-5}$	1.0
Chalk	19	$8.64 \times 10^{-2}$	1263	$1.27 \times 10^{-3}$	1.9	$1.0 \times 10^{-5}$	1.0

Table 5 – Properties in HSS soil models (Gasparre, 2005, Hight et al., 2004)

Soil description	Hardening soil model with small-strain stiffness							
	$R_f$	$m$	$E_{50}^{ref}$ , kPa	$E_{oed}^{ref}$ , kPa	$E_{ur}^{ref}$ , kPa	$\gamma_{0.7}$	$G_0^{ref}$ , kPa	$p^{ref}$ , kPa
London Clay A3	0.9	0	6000	6000	110000	$3.0 \times 10^{-4}$	65000	170
London Clay A2	0.9	0	8500	8500	145000	$5.0 \times 10^{-4}$	90000	287
Lambeth Group UMC	0.9	1	30000	30000	500000	$1.3 \times 10^{-5}$	580000	394
Lambeth Group LMC	0.9	1	35000	35000	700000	$8.0 \times 10^{-6}$	780000	501

Table 6 – Properties in HSS soil models as high bound

Soil description	Hardening soil model with small-strain stiffness							
	$R_f$	$m$	$E_{50}^{ref}$ , kPa	$E_{oed}^{ref}$ , kPa	$E_{ur}^{ref}$ , kPa	$\gamma_{0.7}$	$G_0^{ref}$ , kPa	$p^{ref}$ , kPa
London Clay A3	0.9	0	80000	80000	160000	$3.0 \times 10^{-4}$	75000	170
London Clay A2	0.9	0	70000	70000	145000	$5.0 \times 10^{-4}$	100000	287
Lambeth Group UMC	0.9	1	200000	200000	500000	$1.3 \times 10^{-5}$	800000	394
Lambeth Group LMC	0.9	1	200000	200000	700000	$8.0 \times 10^{-6}$	950000	501