Thermo-mechanical performance of a geothermal pile system for re-harvesting the energy loss through the basement of a building in cold regions

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ABSTRACT
Geothermal energy piles are bi-functional structural elements that are used to support the building, as well as to operate as geo-heat exchangers for shallow geothermal energy systems. However, broad application of thermo-active piles is hindered due to the underground thermal imbalance. We used a numerical thermal analysis for the example of an institutional building located in Winnipeg (MB) to assess the thermal balance of the ground. The heat exchanger probes inlet temperature of the geothermal energy foundation was chosen to meet the underground thermal balance. In addition, using Thermo-Mechanical (TM) modeling, the impacts of thermal loads on mechanical performance of the geothermal pile foundation was studied. The results showed that the axial stress effective on the pile increased by 8% due to thermal loads. Therefore, to consider thermo-active piles as an alternative for buildings energy supply, further considerations should be made to keep the axial stress induced by thermal loads within the admissible range.

RESUME
Les pieux géothermiques sont des éléments structurels utilisés aussi bien pour soutenir un bâtiment que pour fonctionner comme échangeur géothermique. L’échelle d’application de tels pieux est limitée à cause du déséquilibre thermique dans le sol. Une analyse numérique thermique a été effectuée sur un bâtiment situé à Winnipeg (MB) afin de vérifier l’équilibre thermique du sol. La température d'entrée du fluide de l'échangeur de chaleur dans le pieu géothermique a été retenue comme critère. De plus, en utilisant un modèle Thermo-Mécanique, les effets des chargements thermiques sur la performance mécanique d’un pieu géothermique ont été étudiés. Les résultats ont montré que la contrainte axiale impliquée sur le pieu avait augmenté de 8% en raison des chargements thermiques. Dès lors, afin de considérer les pieux thermoactifs comme une alternative pour fournir l’énergie des bâtiments, il faut envisager de maintenir la contrainte axiale induite par les chargements thermiques dans un intervalle acceptable.

1 INTRODUCTION

The energy consumption has increased all over the world due to the population growth and industrial needs. One of the alternatives to address this increasing energy demand is the application of new technologies to harness the energy stored in the ground due to the moderate temperature of the ground throughout the year (Blum et al. 2010). One of the most promising technologies for the application of renewable geothermal energy is the Ground Source Heat Pump System (GSHP). Such a system consists of a heat pump, ground heat exchangers, and a heat distribution system. The ground heat exchangers (GHEs) can be an open-loop or a closed-loop system and their selection depends on various parameters that impact the feasibility of projects, such as the availability of natural groundwater, ponds or lakes. Despite the simple design and better thermodynamic performance of an open-loop system, environmental regulations restrict the application of this type of GHE. The reason is changes of groundwater temperature during the operation of a GSHP, which further increases the bacterial content and suspended matter in groundwater.

On the other hand, closed-loop systems can be installed horizontally (straight horizontal or spirally horizontal loops placed in trenches) or vertically (U-shaped, W-shaped or spiral loops placed in boreholes) depending on the availability of land and energy demand. The installation costs of vertical and horizontal closed-loop systems can be fairly high depending on the required number of boreholes or dimensions of trenches. To overcome this issue, a rapidly growing construction technology, which integrates the geothermal energy technique into the structural pile foundation system has been developed (Brandl 2006). The geothermal pile operation principle is based on the circulation of a heat carrier fluid in polyethylene pipes embedded in the piles through which heat exchange occurs between the geothermal energy pile and the ground (Bourne-Webb 2009). This energy further feeds the GSHP system so that geothermal energy piles act as heat exchangers in addition to their main function as structural support elements.

Geothermal piles are broadly applied in European countries (Laluoi and Nuth 2006, Brandl 2006, Adinolfi et al. 2018) but in Canada, the application of such foundation systems is not well established and limited knowledge regarding the thermal and mechanical operation exists. In cold regions, the efficiency of GSHP systems may degrade over the initial three to five years of their operation (Hepbasli et al. 2003, Lund et al. 2004, You et al. 2014) due to the occurrence of ground thermal imbalance, which is the term used for the gradual decrease in ground temperature over years because of excessive heat extraction. As the soil temperature decreases, the outlet temperature of the GHE lowers gradually, which contributes to a deterioration of heating performance of the GSHP. Therefore, it is of paramount importance to consider the potential occurrence of thermal imbalance in the ground, i.e. the energy performance, in the design of geothermal pile foundation systems in cold regions.

In urban areas, the ground temperature below a building's base area is fairly high in comparison to open rural areas due to the heat dissipation of buildings through their subgrade enclosure (Ferguson and Woodbury 2004). Such heat can be further re-harvested by a geothermal foundation system which favorably affects the efficiency of the GSHP. Moreover, this additional dissipated heat from the building basement can ameliorate the potential thermal imbalance in the ground. In this regard, Saaly et al. (2019) conducted a study to determine the thermal capacity of a proposed hypothetical geothermal foundation system considering heat loss through the basement of an institutional building.

Geothermal energy piles are subjected to thermal loads due to temperature variations of the heat transfer fluid whose magnitude is a function of the building heating and cooling demand as well as structural performance. Therefore, aside from the energy performance of the system, the impacts of thermal loading on the structural performance of geothermal piles need to be assessed as well. For example, thermal loads cause volumetric expansion and contraction when piles are heated and cooled, respectively. In addition, the thermomechanical properties of soils surrounding the pile foundation are temperature-dependent, which can affect the interaction between the soil and foundation and the mobilized shaft friction at the pile-soil interface. Regarding the thermo-mechanical performance of thermo-active piles, several studies have been carried out to understand the response of single piles as well as pile groups to thermal cycles. For example, Pasten and Santamarina (2014) investigated the effects of the number of thermal cycles on the thermo-mechanical behavior, highlighting that most of the pile displacement occurs in the first few thermal cycles. Dupray et al. (2014) compared the mechanical performance of thermo-active piles in two configurations: 1) a group of piles, only one of which was thermo-activated and 2) a group of thermo-active piles. The configuration in which all piles were heated was suggested due to lower differential settlement compared to the case of one single heated pile in the foundation system. In another work, Di Donna et al. (2014) numerically studied the behavior of one single pile and a group of piles subjected to thermal cycles. The additional thermally-induced compressive stresses were concluded to be significant although still within the admissible range. Adinolfi et al. (2018) assessed the impact of operation strategy on the behavior of one single geothermal energy pile using a finite element numerical analysis. It was concluded that the thermally-induced compressive stress and pile settlement were highly dependent on the duration of the heating and cooling seasons.

In the present work, the mechanical behavior of a single pile of a geothermal energy foundation system, which was designed for space heating of an institutional building in Winnipeg (MB) is studied. The foundation system is subjected to heat dissipation through the below-grade enclosure of the building. To this end, an axisymmetric Thermo-Mechanical (TM) model using COMSOL Multiphysics is developed and analyzed.

2 GEOTHERMAL ENERGY FOUNDATION SYSTEM'S FEATURES

The geothermal energy foundation system belongs to a four story institutional building, the Stanley Pauley Engineering Building (SPEB), with a total base area of 1,150 m^2 located in Winnipeg (MB), Canada. Winnipeg experiences extreme temperature fluctuations that range from average +35°C in summer to −35°C in winter. Consequently, the buildings in Winnipeg usually have high energy requirements (Al-janabi et al. 2019).

Winnipeg soil is mainly composed of fine-grained deposits of Lake Agassiz that are followed by Precambrian basement of bedrock (Ferguson and Woodbury 2004). The building is located in a site whose soil stratification consists of a layer of dark grey clay deposits having a thickness of 2 m overlaying a 14.7 m brown clay followed by a dense layer of till deposits.

The foundation of the building consists of 119 concrete micro-piles designed for ultimate limit state axial resistance of 1000 kN, which are embedded at a depth of -4.25 m below grade. Saaly et al. (2019) proposed a geothermal foundation system in which all 119 piles were considered to be geothermal energy piles and were equipped with heat exchanger pipes. In other words, all piles have been assumed to function as geo-thermal heat exchangers to supply the building's energy demand as presented in Table 1.

Table 1. Monthly heating and cooling loads of the building (Al-janabi et al. 2019).

Month	Heating (MWh)	Cooling (MWh)
January	75	19
February	60	18
March	49	23
April	24	27
May	12	29
June	5	38
July	2	50
August	4	48
September	11	38
October	23	30
November	46	22
December	38	20

To determine the inlet temperature of fluid in the pipes, two main factors have been considered: 1. Meeting the thermal balance of the ground during the heat extraction and rejection over the year, 2: Avoiding freezing at the soil-pile interface. Considering these constraints, the inlet temperature of the heat exchanger fluid entering the closed loop embedded in the pile is determined. Based on the results, up to 41% of the energy demand of the SPEB can be supplied by the geothermal energy foundation without occurrence of thermal imbalance in the ground and soil-pile interface freezing. Given that, the mechanical behavior of a single geothermal pile foundation system of the SPEB is studied in the following sections to facilitate the broad application of such systems in cold regions.

3 THERMO- MECHANICAL MODEL

3.1 Governing Equations

A coupled Thermo-Mechanical model has been applied to assess the mechanical and thermal behavior of one of the piles of the Stanley Pauley Engineering Building's foundation. The governing equations for investigation of the mechanical behavior as well as heat transfer phenomena in solid domains are based on the following assumptions:

- Soil is considered to be fully-saturated having two-phases (solid skeleton and water), isotropic and linear elastic.
- Pile material is taken to be solid, isotropic and linear elastic.
- Perfect contact has been assumed at the interface between the soil and pile. This means that relative displacements of pile and soil are ignored.
- The solid grains and fluid phase of the soil are modeled as incompressible materials.

Considering the above-mentioned assumptions, the governing equations are as follow:

$$\nabla . \boldsymbol{\sigma} + \boldsymbol{b} = 0 \qquad [1]$$

where $\nabla .$ is the divergence operator, $\boldsymbol{\sigma}$ is the total (Cauchy) stress tensor and $\boldsymbol{b}$ is the body force vector which can be determined as shown below:

$$\boldsymbol{b} = \rho \mathbf{g} \qquad [2]$$

Where $\mathbf{g}$ [m/s^2] is the gravity vector and ρ [kg/m^3] is the total density whose value for the soil domain can be determined as follow:

$$\rho = (1-n)\rho_s + n\rho_w \qquad [3]$$

where, ρ_s [kg/m^3] is the density of solid grain, ρ_w [kg/m^3] is the fluid density, and n [-] is the porosity of the soil.
The effective stress can be determined as described in Eq 4.

$$\boldsymbol{\sigma}' = \boldsymbol{D}^e(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{\boldsymbol{T}}) \qquad [4]$$

where $\boldsymbol{D}^e$ is the elastic tensor, $\boldsymbol{\varepsilon}$ is the strain tensor, and $\boldsymbol{\varepsilon}^{\boldsymbol{T}}$ is the thermal strain tensor which can be calculated as follows:

$$\boldsymbol{\varepsilon}^{\boldsymbol{T}} = \frac{1}{3}(\alpha_s \nabla T)\boldsymbol{I} \qquad [5]$$

where $\boldsymbol{\varepsilon}^{\boldsymbol{T}}$ is the thermal strain tensor, $\boldsymbol{I}$ is the second order unit tensor, α_s [K^{-1}] is the volumetric thermal expansion coefficient, T [K] refers to temperature, and ∇ is the gradient operator.

To determine the heat transfer in porous media, the energy conservation equation is applied:

$$\rho C \frac{\partial T}{\partial t} + \nabla . q_c = 0 \qquad [6]$$

where ρC [J/m^3°C] is the volumetric heat capacity of the soil which is a function of volumetric heat capacity of solid skeleton ($\rho_s C_s$) and pore water ($\rho_w C_w$) as described below:

$$\rho C = (1-n)\,\rho_s C_s + n\,\rho_w C_w \qquad [7]$$

also, q_c [W/m^2] is the conductive heat flux through the volume which is defined by Fourier's law as follows:

$$q_c = -\lambda \nabla \mathrm{T} \qquad [8]$$

where λ [W/m°C] denotes the thermal conductivity of material whose value for the soil can be determined as described in Eq. 9.

$$\lambda = (1-n)\,\lambda_s + n\,\lambda_w \qquad [9]$$

where λ_s is the thermal conductivity of solid grains and λ_w is thermal conductivity of water.

3.2 Numerical Model

The time-dependent numerical model has been implemented in the finite-element commercial software COMSOL Multiphysics. The axisymmetric soil domain dimension is 10 m × 10 m. On top of the soil domain, a 0.23 m thick layer of thermal insulation and a 0.2 m thick layer of concrete slab are placed. The modeled pile has a radius of 0.2 m and a length of 5 m. The thermal properties of soil (for saturated conditions) as well as concrete and insulation applied in the model are chosen according to Bobko et al. (2018) as summarized in Table 2. The mechanical properties of material have been selected according to Bourne-Webb et al. (2009).

Based on the structural and design documents, 5 m micro-piles have been used in the foundation of the Stanley Pauley building considering the structural load and geotechnical parameters.
Figure 1 shows the geometry of the computational model. The boundary conditions of the TM model are as follows:

- The thermal boundary conditions: constant temperature on the heat exchanger, adiabatic condition at the bottom and surrounding boundaries. Also, to estimate the impacts of heat dissipation through the building's basement slab, a convective heat flux q [w/m^2] has been assigned to the top boundary of the model as follows:

$$q = h\,(T_{indoor} - T_s) \qquad [10]$$

  where h is the convective heat transfer coefficient whose value is assumed to be equal to 6 [W/m^2°C] (Liu et al. 2019), T_{indoor} is the basement's indoor air temperature that is assumed constant and equal to 20°C, T_s is the slab's surface temperature.
- The mechanical boundary condition: the roller condition on the right boundary of the model, axial symmetry condition on the left boundary, and fixed constraint at the bottom of the domain.

The initial temperature of the model has been assumed to be equal to 8°C [Saaly et al. 2019]. Also, the initial stress condition is obtained from the results of another steady-state simulation considering only the gravity effects.

Table 2. Properties of SPEB's numerical model.

Soil	
Young's modulus [Pa]	70×10^6
Poisson ratio [-]	0.236
Density [kg/m^3]	1767
Thermal conductivity [W/m°C]	1.483
Specific heat capacity [J/kg°C]	1873
Thermal expansion coefficient [K^{-1}]	1.7×10^{-5}
Porosity [-]	0.535
Concrete	
Young's modulus [Pa]	40×10^9
Poisson ratio [-]	0.2
Density [kg/m^3]	2300
Thermal conductivity [W/m°C]	1.8
Specific heat capacity [J/kg°C]	880
Thermal expansion coefficient [K^{-1}]	8.5×10^{-6}
Insulation	
Density [kg/m^3]	34
Thermal Conductivity [W/m°C]	0.041
Specific heat capacity [J/kg°C]	1450

3.3 Model Validation

To validate the proposed TM model in this work, the obtained results have been validated against the experimental data provided by Bourne-Webb et al. (2009). This study has been conducted on London clay whose properties are reported in Table 3. The tested pile had a diameter of 0.6 m and a length of 23 m.

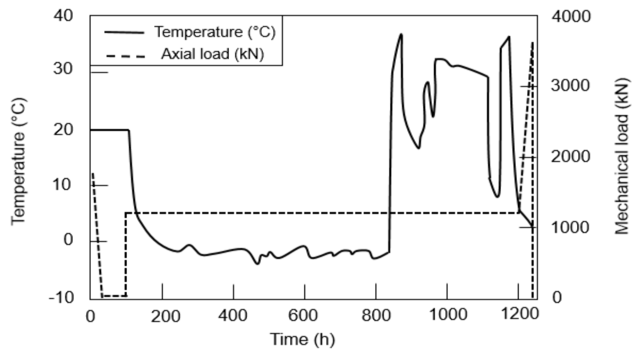

Figure 1 Thermo-mechanical loading history of the experimental case (Bourne-Webb et al. 2009).

The initial temperature of the pile and soil in the London case was assumed constant over the entire domain and equal to 19.5°C and the thermo-mechanical loading time applied in this study lasts for almost 1,250 days.

Table 3. Characteristics of validation model's material

Property	Concrete	London Clay
Young's modulus [Pa]	40×10^9	70×10^6
Poisson ratio [-]	0.2	0.236
Density [kg/m^3]	2550	2038
Thermal conductivity [W/m°C]	2.33	1.79
Specific heat capacity [J/kg°C]	960	910
Thermal expansion coefficient [K^{-1}]	8.5×10^{-6}	4.0×10^{-5}
Porosity [-]	-	0.4

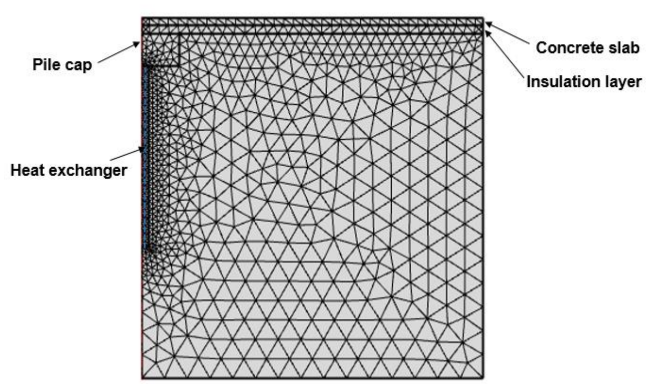

Figure 2. Axisymmetric finite element model.

The conducted tests include both heating and cooling cycles in conjunction with a mechanical load. The test pile is designed as a friction pile subjected to an axial load equal to 1,200 kN incorporated with thermal cycles using a heat transfer fluid whose temperature varies between -6°C and +40°C (Figure 2). The thermal pile's response to the applied thermo-mechanical loads has been shown in Figure 3.

The numerical results obtained from the TM model show a good agreement with the experimental data reported by Bourne-Webb et al. (2009) especially for the mechanical and cooling loads (100-860 h) (Fig. 3). Although the magnitude of vertical displacement of the pile head during the heating + mechanical loading is slightly lower in the numerical model, the similarities are acceptable from an engineering point of view to consider the model an appropriate tool for predicting the thermo-mechanical behavior of the geothermal energy pile.

3.4 Thermo-Mechanical Loading History of the Geothermal Energy Pile in SPEB

The validated numerical model in COMSOL Multiphysics has been applied to investigate the behavior of one of the geothermal piles of the SPEB's foundation. The total loading time lasts for 1,825 days which includes seasonal cyclic thermal loads (i.e., cooling and heating) in conjunction with a constant mechanical load which is equal to the nominal resistance of the pile applied with resistance factor of 0.35.

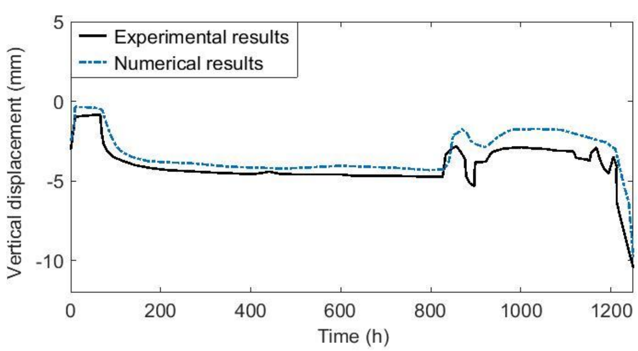

Figure 3. Comparison between the numerical and field data regarding the vertical displacement of the pile head.

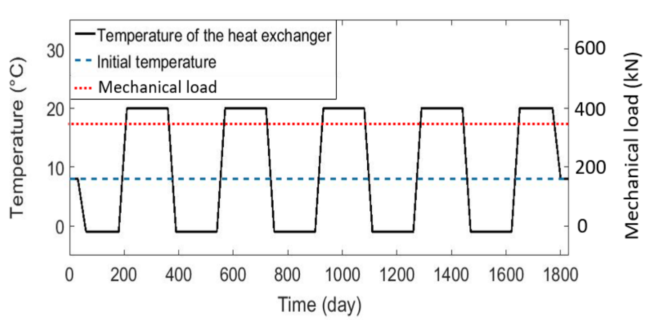

Figure 4. Seasonal temperature variation of the pipes (Saaly et al. 2019).

As mentioned earlier, the thermal load is applied to the pile while the heat transfer fluid circulates in the heat exchanger pipes. In this work, such thermal load is represented by a constant temperature, which is equal to the inlet fluid temperature of the heat exchanger pipes, along the length of the heat exchanger pipe. Based on the numerical study carried out by Saaly et al. (2019), the inlet temperatures of the pipe have been suggested to be equal to 20°C during May-Oct, and -1°C during the 6 cold months (Nov-Apr) of each year. As mentioned before, the inlet temperatures were chosen to meet the thermal balance of the ground during heat extraction and rejection over the year as well as to avoid freezing at the soil-pile interface. Figure 4 provides the seasonal variation of the inlet temperature at the heat exchanger probes.

4 RESULTS

To make sure the thermo-active pile is applicable from geothechnical point of view, the vertical displacement of the piles as well as the maximum axial load induced by the thermal load is studied in this section.

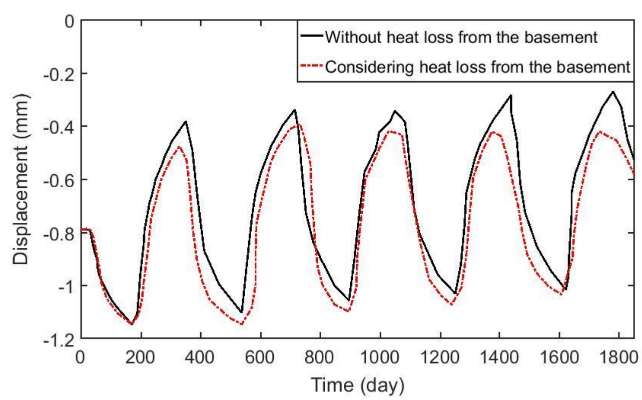

Figure 5. Vertical displacement of the pile head with and without consideration of the heat leakage from the basement slab.

The vertical displacement variation of the pile head has been shown in Figure 5. To better understand the initial settlement of the pile as a result of the mechanical load, during the first 30 days of the simulation time history, only the mechanical load is applied on the pile head. As shown in Figure 5, the initial pile head displacement induced by the mechanical load is equal to -0.79 mm. Once the cooling phase begins, further pile head displacement occurs whose maximum reached at the end of the cooling season (-1.15 mm). Such observation is induced due to the contraction of the pile as a result of temperature decrease in the pipes. In contrast, during the heating period (May-Oct), the geothermal pile expands upon the temperature increase. The maximum expansion, +0.46 mm relative to the initial settlement, happens at the end of October that is the end of the cooling season. During the last 30 days of operation of the system (i.e. at the end of fifth year of the system operation), the pipe temperature has been set equal to the initial temperature of the pile (8°C) to evaluate the reversibility of displacements induced by thermal loads. It can be observed that the thermal displacements were not fully reversible and results showed presence of 22% residual displacement in the pile due to thermal loads. It should be mentioned that if the heat loss through the basement is disregarded, the pile head displacement increased up to 17% compared to the case with basement heat loss. This happens since the dissipated heat generates additional expansion in the pile especially at the depths near the basement level.

The distribution of mobilized shaft friction has been shown in Figure 6. During the mechanical loading stage, the direction of the skin friction is upward and decreases with depth. However, as the heating season begins, the mobilized shaft friction along the length of the pile upper than the neutral point increases while along the length of pile lower the neutral point decreases due to contraction of the concrete pile. Conversely, during the cooling season that expansion occurs in the pile, mobilised shaft friction increases along the length of the pile lower than the neutral point while along the upper part of the pile decreases compared to mechanical loading stage.

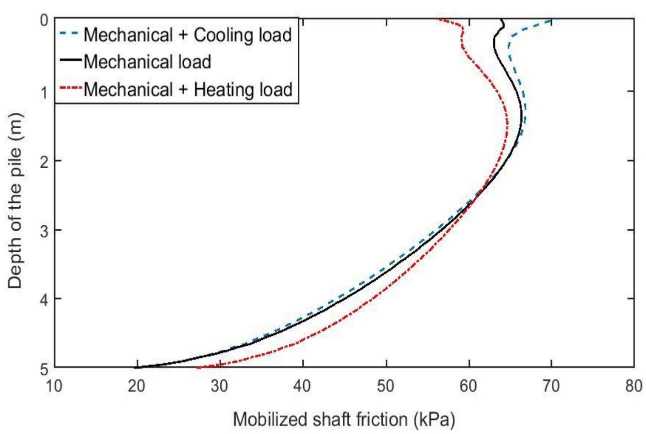

Figure 6. Mobilized shaft friction along the length of the pile.

The axial load distribution along the pile axis has been shown in Figure 7. According to the results, in the stage in which the pile is subjected to only mechanical load (t=30 days), the pile is fully compressed. However, the contraction in winter mode induces tensile forces in the pile. Therefore, the axial load along the pile decreases compared to the only mechanical loading stage. At time t=365 days at which the heating season ends, the pile has expanded and an increase in compressive load to the maximum value of 360 kN can be observed along the length of the pile.

The axial load distribution provided in Figure 7 signifies that the thermal cycles change the magnitude of the axial load effective on the pile. In other words, the heating load (i.e., *ΔT=+12°C)* increases the effective axial load on the pile up to 8%. To fulfil the safety of application of a geothermal pile, such increase in the load effective on the pile should be implemented in the geotechnical design by considering the pile for higher nominal resistance or by decreasing the resistance factor.

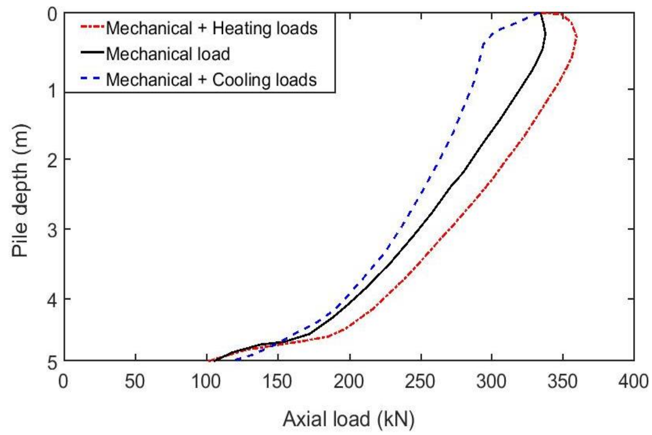

Figure 7. Variation of axial load along the pile axis.

5 CONCLUSION

Geothermal energy piles are structural elements which also serve the function of geo-heat exchangers. In cold regions where the heating load is commonly higher than the annual cooling load, the thermal imbalance may occur in the ground. The optimum thermal performance of geothermal energy pile system avoids freezing at the pile-soil interface as well as the underground thermal imbalance. However, aside from the thermal performance of the geothermal pile system, the mechanical behavior of such piles needs to be investigated as well.

This study was intended to evaluate the mechanical behavior of a single pile within the geothermal energy foundation system which is designed for supplying the energy demand of the Stanley Pauley Engineering Building on the Campus of the University of Manitoba, Winnipeg, Canada. To this end, an asymmetrical TM model was developed in COMSOL Multiphysics and was validated against the experimental data obtained from the tests in the Lambeth College in London. Based on the numerical analysis, the following conclusions can be made:

- The pile head downward displacement due to the cooling stage increases up to 42% (i.e., up to 1.15 mm) compared to mechanical loading stage. Such settlement is far below the allowable pile settlement that is equal to 25 mm (CGS 2006).
- Heating load applied to the pile increases the axial load effective on the pile by up to 8% compared to the axial load induced by only mechanical load. This should be considered in the geotechnical design of the pile. This consideration can be implemented in the form of increasing the factor of safety effective on the allowable load.

This study provides an insight into the mechanical behavior of a single pile of a geothermal energy pile system. The results of this study in conjunction with the thermal performance analysis can facilitate further application of such systems in cold regions.

6 ACKNOWLEDGEMENT

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