Application of Thermal Piles in Thawing a Frozen Ground

G. Sinnathamby*
**Geoengineering, Department of Civil & Environmental Engineering, Aalto University, Finland*
gowthaman.sinnathamby@aalto.fi

H. Gustavsson[&], L. Korkiala-Tanttu[&], C.P. Cervera[$], M.Koskinen[#]
[&]*Department of Civil & Environmental Engineering, Aalto University, Finland*
[$] *Fundación Valenciport, València, Spain*
[#] *City of Helsinki, Finland*

ABSTRACT

The thawing of the frozen ground below an ice rink facility in Myllypuro, eastern Helsinki, Finland was studied in detail through analytical approach and numerical simulations. A malfunction in the floor-heating system caused freezing conditions in the ground underneath. Over the years, frost heave caused significant deformations to the facility and, in 2012 forced an immediate renovation. During the renovation, the existing old foundation was replaced with a new foundation system comprised of a well-insulated concrete floor-slab and a group of around 240 steel thermal piles. Thermal piles were preferred in this case because the frozen ground surrounding individual piles needed to be thawed, hence a direct contact between the soil and the pile shaft can be prevented. This reduces the possible risk of additional load from the frozen ground being applied on the piles.

As part of the ongoing monitoring programme, a thermal modelling of the thawing process was carried out with commercially available SoilVision Heat (version 2.4.10) software programme. The primary objective of this study was to model the thawing process numerically and therefore, the time needed to thaw the frozen ground can be estimated. Upon complete thawing, establishing the required constant temperature that needs to be maintained in the piles in order to prevent the ground from re-freezing was another objective. The ground temperature profiles obtained from the model simulations were compared with in situ temperature measurements as the thawing progresses. The time needed for complete thawing of the frozen ground from the simulations is in good agreement with analytical estimations and in situ observations. The thermal modelling shows that once the frozen ground is completely thawed, a heat injection at around +7°C by the piles is sufficient to prevent the ground from re-freezing.

Keywords: Thermal Modelling; Thaw Settlement; Thermal Piles; Freeze and Thaw; SVHeat.

1 INTRODUCTION

This paper presents the results of a case-study in which steel thermal piles were used to thaw a frozen ground below the Myllypuro ice rink facility (hereinafter referred to as MIR) in eastern Helsinki, Finland. MIR was built in 1976 in order to facilitate winter (ice) sports initially during autumn and spring seasons; however, since 1980's, the facility has been used throughout the year (Vähäaho et al., 2012). Figs. 1a and b show the plan and sectional views of the MIR, respectively. The facility was founded on a clay deposit by incorporating a 100 mm thick expanded polystyrene (EPS) floor-insulation and a heat wire system in order to prevent the ground from freezing and ultimately from frost heave. Over the years, a malfunction in the floor-heating system lead to freezing of the ground below the ice rink as the thin EPS insulation was alone not sufficient to prevent the cold front advancing. Furthermore, since the ice rink was in continuous use after

1980's, it prevented the ground from natural thawing during summer seasons. The ground freezing advanced over the years and uneven ground deformations started to appear, leading to increased maintenance costs.

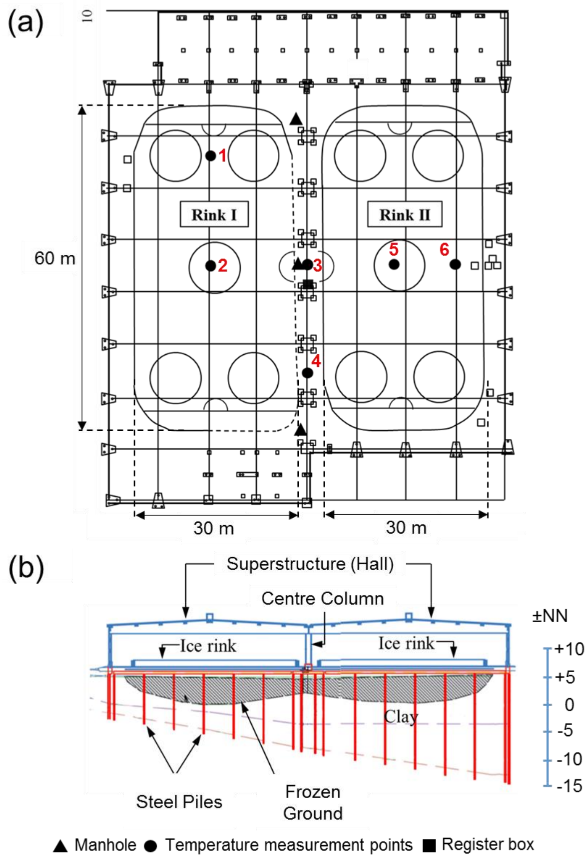


Figure 1. Various observation points at MIR: (a) Plan view and (b) Sectional view (modified from Vähäaho et al., 2012).

In 1996, a monitoring program comprised of several temperature and settlement sensors, and lateral deformation indicators was set up to assess the effects of frost heave. In 2011, the frost heave endangered the structural safety of the MIR by uplifting the centre columns and forced an immediate renovation. In the year 2000, the measured maximum frost depth was around 6.3 m, resembling permafrost conditions (Vähäaho et al., 2012). Deformation measurements taken in 2012 showed that the centre columns in the middle of the hall (Fig. 1b) experienced an uplift of around 88 mm, while a frost heave of around 0.5 m was observed in the centre of the ice rink (e.g. points 2 & 5 in Fig.1a). Furthermore, horizontal movements were also observed. Based on the results from the monitoring program, a renovation of the ice rink was proposed. A new foundation system and a controlled thawing of the contact between the frozen ground and individual piles were incorporated in the renovation. The new foundation system consisted of a well-insulated concrete floor-slab and an array of steel piles (Vähäaho et al., 2012). The piled concrete slab works as a load carrying structure. The concrete slab separates the cooling pipes (the ones used to maintain the icy-surface of the rink) and warming pipes (the ones used to prevent the subsoil from freezing), which are located in the upper and lower parts of the concrete slab, respectively. In addition, a 100mm thick insulation barrier and a drainage system were designed in order to avoid heat transfer between the soil and the cooling system and to keep the structures dry, respectively.

The aim of using thermal piles was to initially thaw the frozen ground only around each piles, hence there would be no contact between the frozen ground and piles. Significant adhesion between the frozen soil and the piles could create excessive negative skin frictions (i.e. additional loading) on the piles. However, the thawing is expected to progress and eventually lead to a complete thawing of the entire frozen ground below the MIR.

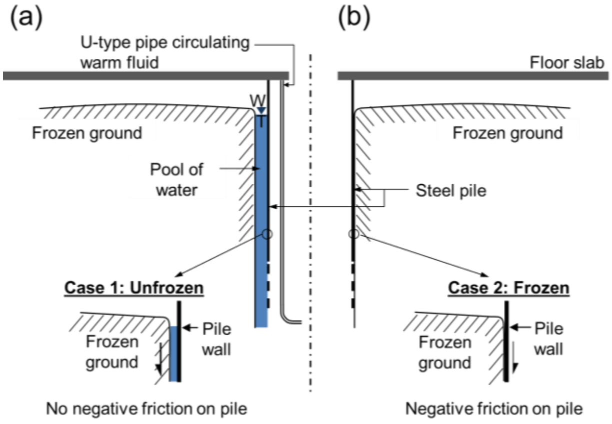


Figure 2. Conceptual figures showing: (a) a thawed frozen ground around a pile that injects heat, and (b) a frozen ground around a pile that does not injects heat and thus, developed negative skin friction along its shaft (not to scale).

Consequently, the number of piles required (and hence renovation costs) would have increased in excess (Fig. 2). The objective of this study was to model the thawing process numerically and to estimate the time needed to thaw the frozen ground around the piles completely. Establishing the required constant temperature that has to be maintained in the piles (of the warming liquid) in order to prevent the ground from re-freezing was another objective.

Several 2D and 3D transient model simulations were run with commercially available SVHeat (version 2.4.10) software programme and the modelling results were compared with analytical estimation of the time required to thaw the ground completely, and also with several in situ temperature measurements.

2 ANALYTICAL APPROACH

The time needed for the complete thawing of the frozen ground was first analytically estimated. The results from the analytical approach are then used to validate the results from numerical simulations. Assuming a 5 m average frozen depth based on the in situ measurements, the total volume of the frozen ground below the ice rink (V_f) is around 23760 m^3 (i.e. *Length* x *Width* x *avg. Depth* = 72 x 66 x 5 m^3). As a first step to the thawing process, the temperature of the frozen ground needs to be raised to 0°C. Considering – 3°C as the average temperature of the frozen ground and the volumetric heat capacity of the frozen ground as 2000 kJ/ m^{3}K, the total heat energy required to raise the ground temperature from – 3°C to 0°C, q_1, can be calculated from Eq.1.

$$q_1 = V_f \, C_i \, \Delta T \qquad (1)$$

$$q_2 = w_{vol} \, L_f \qquad (2)$$

where V_f is the volume of the frozen ground (in m^3), C_i is the volumetric heat capacity of the frozen soil (in kJ/m^{3}K), L_f is the volumetric latent heat of fusion of water (in J/m^3) and ΔT is the change in temperature (in K). Therefore, from Eq.1, the total heat energy required for this phase is around 143 GJ (≈ 40 MWh) (i.e. 23760 x 2000 x [0-(-3)] = 143 GJ.

The next step is to calculate the heat energy required for the phase change from ice to water at 0°C, q_2, and can be calculated from Eq.2. Taking the average volumetric water content of the soil as 60 %, w_{vol} is 14256 m^3 (i.e. w_{vol} = 23760 x 0.6 m^3). If L_f is 3.34 x 108 J/m^3, then from Eq.2, q_2 is around 4762 GJ (1323 MWh) (i.e. 14256 x 3.34 x 108 ≈ 4762 GJ). Therefore, the total amount of heat energy required (q_1 + q_2) for the complete thawing of the frozen ground is around 1363 MWh.

The total energy injection can be calculated by measuring the actual inlet and outlet temperatures of the warming fluid, and pressure values (to determine the rate of flow of the warming liquid). The energy that is injected per second (i.e. power) can be calculated from Eq. 3, while the total energy injected can be calculated from Eq. 4.

$$P = Q \times C \times (T_{in} - T_{out}) \qquad (3)$$

$$E = P \times t \qquad (4)$$

where P is the power (in *kW*), Q is the rate of flow of warming liquid (in *l / sec*), C is the specific heat capacity of the warming fluid (in *kJ/kg-K*), T_{in} is the inlet temperature (in *K*), T_{out} is the outlet temperature (in *K*), E is the energy (in *kW*) and t is the effective operational time of the heat pump (in *sec*).

In situ measurements of the warming liquid showed that the rate of flow was around 4 *l/sec*, and the inlet and outlet temperatures were around +28°C and +20°C, respectively. If a specific heat capacity of 3.5 *kJ/kg-K* is assumed for the warming liquid, the estimated energy injection by the system per second would be around 112kJ (i.e. from Eq.3, P = 4 x 3.5 x [ΔT=8]). Hence, by taking 18 hours of effective daily operation of the heat pump, the total energy injected in one year would be around 735 MWh (Eq. 4), which is less than the total energy required

(1363 MWh). Therefore, more than one year (≈ 680 days) of heat injection is required by the piles in order to thaw the frozen ground completely.

Applying the same calculation for the influence area of one pile (i.e. 5.5 m x 5.5 m) and considering an equal average frozen depth of 5 m, the total number of days required for complete thawing is around 750 days. As the frozen volume of the ground below the MIR is not precisely known, the calculation are done based on realistic assumptions. Hence the results are only approximate; however, the calculations based on the effective area of one pile may better represent the real scenario and is compared with the numerical simulation results later in this paper.

3 THERMAL MODELLING

3.1 Model Geometry, Limitations and Characteristics

The thawing process of MIR was studied numerically with commercially available SoilVision Heat v 2.4.10 software program (herein referred to as SVHeat). SVHeat is capable of modelling various heat transfer mechanisms in soils under saturated and unsaturated conditions. It is also able to model geothermal gradients and the movement of freezing fronts with advanced boundary conditions under steady-state and transient thermal conduction and convection conditions (Thode, 2013).

Two different SVHeat models were created in this study with two distinct objectives: first one was a 2D transient model, simplifying the entire cross section of the ice rink and the other one was a 3D transient model representing the influence area of a single pile. The objective of the 2D model was to study the change in ground temperature profile with time in a bigger scale, while the 3D model investigated the ground temperature profile around a single pile.

The modelled single pile represented the worst-case-pile scenario, i.e. a pile remotely located (at the edge) in the pile-group, where the frozen ground could take longer to thaw because further inside the pile-group, the influence of the heat injection from adjacent piles is significantly higher than that of the remotely located piles, therefore the thawing would be relatively faster. Thus, studying the influence area of a pile located away from the centre of the ice rink (i.e. at the edge of the pile-group) is more appropriate for the monitoring of the worst-case thawing scenario.

The modelling of the entire thawing process was carried out in three phases. At first, initial conditions existed right before the renovation, were established with a steady-state analysis based on the measured in situ temperature data. From this analysis, the ground temperature profile and the frost depth below the ice rink were obtained and validated with the results obtained from the SSR model (Sinnathamby et al., 2015; Sinnathamby et al., 2016). The ground temperature profiles obtained from this phase was used as the initial condition for the subsequent phase of the modelling.

In the second phase, a 1000-day long medium-term transient analysis was carried out, simulating the ground thermal evolution and the thawing process since the facility was reopened after the renovation in December, 2012. During this period, it was assumed that the thermal piles were injecting heat at +20°C (same as the outlet temperature of the warming liquid), resulting in a constant heat injection of 112 kJ per second. In this phase, two different boundary conditions were used for the piles, first one is a constant temperature boundary condition (CTBC) and the second is a constant heat flux boundary condition (CHFBC) (see section 3.3.1).

In the final phase, a 10 year-long transient analysis was carried out with a CTBC on piles. The main objective of the final phase was to determine the required constant temperature that needs to be maintained in the piles in order to prevent the ground from re-freezing. The SVHeat 2D and 3D model geometries are shown in Fig. 3.

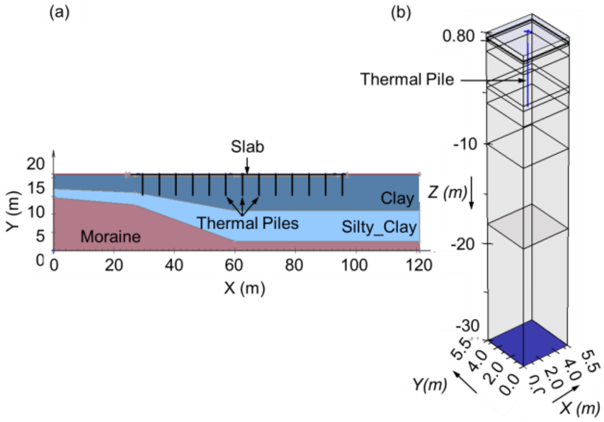


Figure 3. SVHeat model geometries: a) 2D model representing the entire cross section, and b) 3D model representing a single pile and its influence area.

3.2 Materials

The soil profile under the ice rink was divided into three layers, namely clay, silty-clay and moraine (from top to bottom). The average material properties used in the models are shown in Table 1. The thermal properties of the soils were obtained from laboratory tests carried out on in situ soil samples collected from the site (Sinnathamby et al., 2015; Sinnathamby et al., 2016; Cervera, 2013) and also from the literature (Sundberg, 1988; Clauser, 2006; Andersland et al., 1994).

In the 2D models, the thermal conductivity used in the clay layer was calculated as the average of the values obtained in the laboratory test in order to simplify the model and to reduce the simulation time. On the other hand, in the 3D models, the clay layer itself was subdivided into 6 layers with different thermal properties obtained from the laboratory tests in order to get more accurate results. Due to the low-permeable subsoil conditions, no groundwater seepage was considered. The thermal properties of other construction materials such as the concrete slab and the floor-insulation are also presented in Table 1.

Table1. Thermal properties of the materials for the 2D model

		Thermal conductivity, λ (W/m K)	Heat capacity, C_i (KJ/m³K)	Vol. Water content, w_{vol} (m³/m³)
SOIL				
Clay	UF[1]	1.07	2400	0.675
	F[2]	2.46	2000	0.675
Silty-clay	UF	1.75	3000	0.366
	F	3.00	2000	0.366
Moraine	UF	3.01	2700	0.050
	F	3.36	2000	0.050
CONSTRUCTION MATERIALS				
Concrete	UF	1.63	2300	0.1
	F	2.50	2000	0.1
XPS	UF	0.035	52.5	0.01
	F	0.035	52.5	0.01

[1]Unfrozen; [2]Frozen

Freezing and thawing processes and the water phase change (from ice to water) in fine-grained soils are related to the unfrozen water content and to the freezing curve. The freezing curves and realistic residual unfrozen water content in this study were obtained from the existing data in the literature (e.g. Thode & Fredlund, 2012).

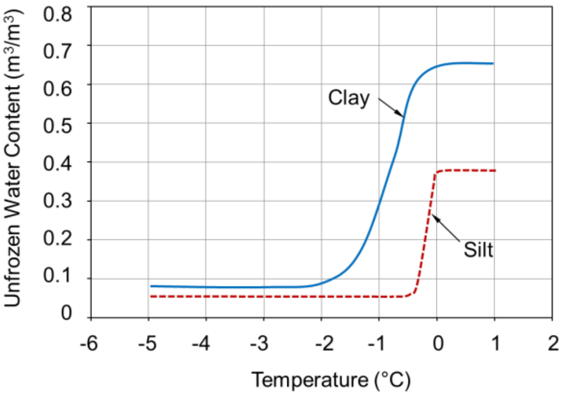


Figure 4. Unfrozen water content curves of clay and silt used in the models (Modified from Thode & Fred, 2012)

It was found that the residual unfrozen water content of the clay and silt varied between 8% - 13% and 5% - 7%, respectively (Thode & Fredlund, 2012; Liu & Li, 2012). The characteristic unfrozen water content curves of different soil layers were calculated as an exponential function according to these unfrozen water content values. Fig. 4 shows the characteristic unfrozen water content curves and their residual values of clay and silt that are used in the models.

3.3 Boundary Conditions

3.3.1 Constant Boundary Conditions

The following constant boundary conditions were used in the transient models carried out:

Piles (BC4)

The piles were modelled with well boundary condition in which the heat is injected along the perimeter of the pile. Two different models were created with different boundary conditions for comparisons with the in situ conditions. Firstly, a Constant Temperature Boundary Condition (CTBC) was used for the piles in which the temperature along the pile perimeter is constant throughout the simulation.

Secondly, a Constant Heat Flux Boundary Condition (CHFBC) was applied on piles, which means that the pile injects a constant heat flux but the temperature in the pile surface could vary with time as the ground temperature changes. The length of the piles varied between 15 m to 20m, but the depth of the embedment of warming tubes inside the piles was only around 6 m to 7 meters, depending on the frozen depth, and therefore, the piles were modelled up to this depth. Piles in the 2D models were modelled with CHFBC, while the single pile in the 3D model was modelled with both CHFBC and CTBC.

3.3.2 Variable Boundary Conditions

A. Water pool temperature function (BC5)

A pool of water below the ice rinks was noticed during the insitu observations in 2012. The depth of the pool was around 1.3 m from the ground level and presumably resulted from the thawing of the frozen ground. This water was heated due to the energy injection by the piles. Therefore, a boundary condition was used to represent the temperature of this pool of water (Fig. 6a). The water temperature function was calculated from the averages of in situ temperature measurements taken from three observation manholes below the ice rink. An assumption was made that the last measured in situ temperature of + 5.4°C would remain constant during the transient analysis. This boundary condition was applied between the bottom of the concrete slab and the top of the clay layer in the models.

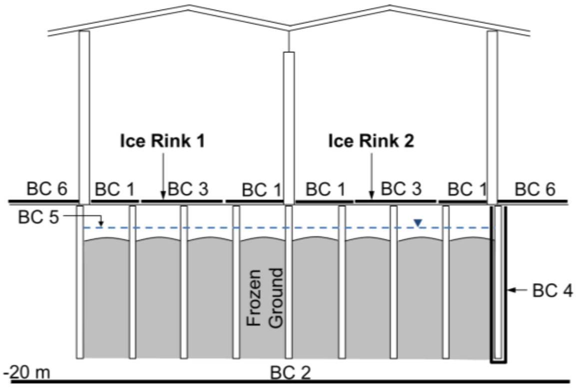
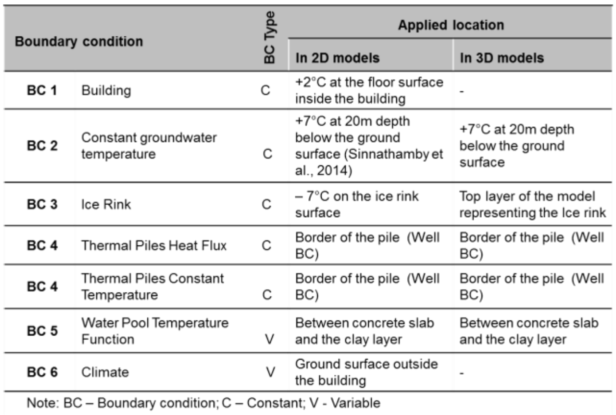


Figure 5. Schematic showing the applied boundary conditions (not to scale)

Table 2. Boundary conditions that are applied in the models



Boundary condition		BC Type	Applied location	
			In 2D models	In 3D models
BC 1	Building	C	+2°C at the floor surface inside the building	-
BC 2	Constant groundwater temperature	C	+7°C at 20m depth below the ground surface (Sinnathamby et al., 2014)	+7°C at 20m depth below the ground surface
BC 3	Ice Rink	C	– 7°C on the ice rink surface	Top layer of the model representing the Ice rink
BC 4	Thermal Piles Heat Flux	C	Border of the pile (Well BC)	Border of the pile (Well BC)
BC 4	Thermal Piles Constant Temperature	C	Border of the pile (Well BC)	Border of the pile (Well BC)
BC 5	Water Pool Temperature Function	V	Between concrete slab and the clay layer	Between concrete slab and the clay layer
BC 6	Climate	V	Ground surface outside the building	-

Note: BC – Boundary condition; C – Constant; V - Variable

B. Climate function (BC6)

A climate function represented the influence of the climate (air temperature) in the thawing process (Fig. 6b). The climate function was estimated based on the mean monthly temperature data of Helsinki, collected over the past 30 years (Pirinen et al., 2012). The climate function was applied as a cyclic function on the ground surface outside the building in the 2D model and repeated annually during the entire transient analysis. Effect of snow cover and/or solar radiation on the surface temperature was not considered. Table 2 and Fig. 5 summarize the boundary conditions used in 2D and 3D models, and their applied locations in the models.

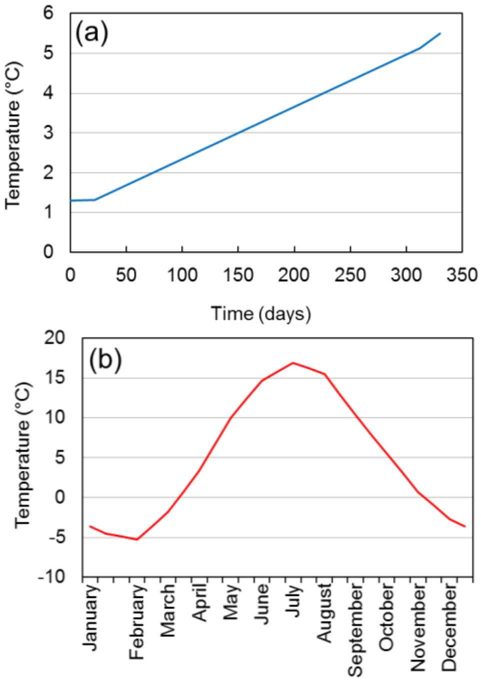


Figure 6. Boundary conditions: (a) Temperature function of the pool of water, and (b) Cyclic climate function of Helsinki (Pirinen et al., 2012).

4 RESULTS AND DISCUSSIONS

4.1 *Thawing Process*

4.1.1 *Initial conditions: Steady-state*

The initial steady-state analysis was done in order to establish the existing conditions below the ice rink in Myllypuro right before the renovation. The results from the SVHeat models showed that the maximum depth of the frozen soil varied between 6.5 m and 7 m. The frozen soil depth and the soil temperature profiles obtained from these SVHeat models were similar to the in situ observations made, and thus, validating the model.

4.1.2 *Transient Analysis*

A. Constant Temperature Boundary Conditions (CTBC): 3D Model

The second phase of the modelling represented the thawing of the frozen ground, starting from the day when the facility was re-opened in December 2012 after the renovation. In this analysis, it was assumed that the piles were injecting heat into the ground at +20°C, at a temperature equivalent to the measured outlet temperature of the warming fluid. Fig. 7 shows the ground temperature evolution at different depths during the transient analysis. From Fig. 7, it can be seen that around 400 – 450 days are needed to thaw the frozen ground across the entire depth. The results obtained with the 3D model are in good agreement with the in situ temperature measurements. The results obtained from the 3D model also validate the preliminary analytical calculations that showed more than one year of heat injection is required in order to thaw the frozen ground completely.

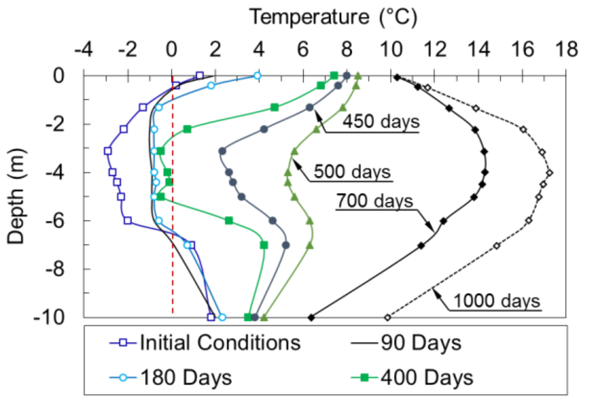


Figure 7. Ground temperature profile from the 3D model under CTBC at different stages of the thawing process in points located in the middle of two piles (d =2.75m).

A ground temperature increase from – 3°C to – 1°C within the frozen depth (0.5 – 6.0 m) can be noticed as soon as the heat injection started (within around 30 days) (Fig. 7). However, it took nearly 400 – 450 days to reach positive temperatures (from – 1°C to – 0°C) within the frozen depth. This was primarily attributable to the phase change of the frozen water and the amount of unfrozen water content presence in the soil. Compared with the preliminary analytical calculations, the results from the 3D model with CTBC showed that around 300-350 less days are required for complete thawing. Fig. 8 shows the temperature evolution of the ground surrounding the pile at different time steps.

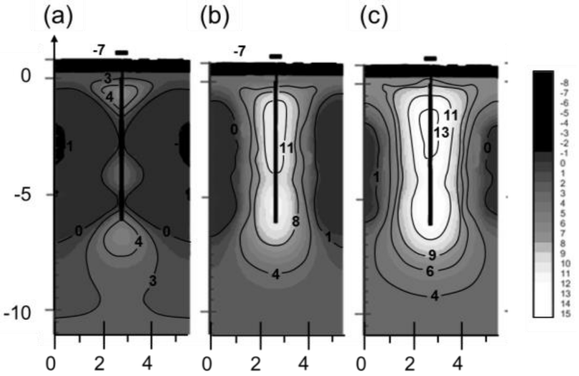


Figure 8. Ground temperature evolution after: (a) 30, (b) 180 and (c) 365 days.

B. Constant Heat Flux Boundary Conditions (CHFBC): 2D and 3D models

Due to the significant discrepancies between the CTBC model results and analytical estimation of the time required to thaw the frozen ground, a new boundary condition was introduced with constant heat flux (CHFBC) of around 112 kW for 240 piles (40320 kJ/day-pile) (Eq.1). Fig. 9c shows the results obtained with the CHFBC boundary conditions and can be noticed that more than 800 days are required for complete thawing of the frozen ground. The results obtained with the CHFBC are in good agreement with the preliminary analytical calculations done based on the influence area of a single pile. The time needed to reach the steady-state in the model and the energy losses through the pile materials (which were not considered in the models) could be the reason for the discrepancies between the model results. Fig. 9b shows the in situ temperature measurements taken from a point near the edge of the ice rink (remote location) and can be compared with the CHFBC results in Fig. 9a.

Similar results in a larger scale was achieved in the 2D model as well. In the 2D model, the total heat flux injected by the piles was divided by the distance between the pile rows (5.5m) in order to get the average energy injected per model-meter.

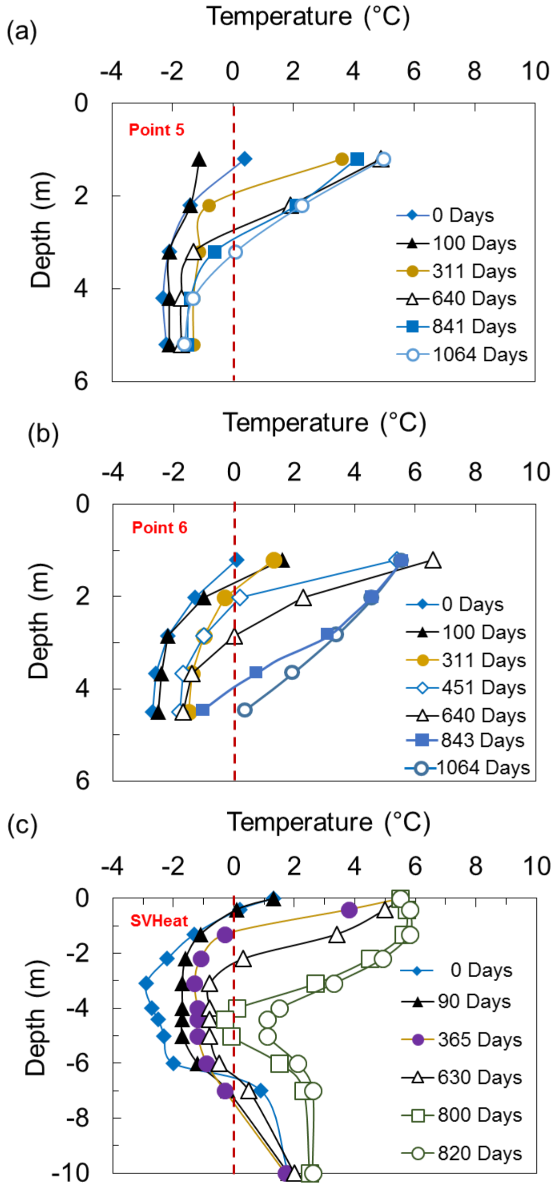


Figure 9. Ground temperature profiles: In situ measurements from (a) point 5 (in the middle of the ice rink; Fig 1a), (b) point 6 (at the edge of the rink: Fig. 1a), and (c) SVHeat (3D model) with CHFBC in points located in the middle of two piles (d=2.75m).

4.2 Modelling the Target Temperature on Pile Surface with CTBC

Final step of the analysis was to establish a constant temperature in the piles that is required to prevent the surrounding thawed soil from re-freezing. This constant temperature has to be as low as possible for efficient energy consumption. Therefore, in order to determine the required target temperature, several models were done with a range of temperatures on the piles at +20°C,

+15°C, +10°C and +7°C. The soil temperature profile obtained in the previous step after 1000 days of heat injection at 112kW (phase 2) was used as the initial condition for these models.

The analysis results showed that once all the ice below the ice rink is melted, heat injection at a minimum temperature of around +7°C is sufficient to prevent the ground from refreezing. It is important to note that in the models, the piles were modelled as a well boundary condition, which means that the piles were modelled as an empty cylinder and their physical and mechanical properties were not considered. Considering this, the target temperature should be at least +7°C at the border of the pile. This means that the temperature of the warming liquid circulating inside the piles should be higher because there would be thermal losses through the pile material.

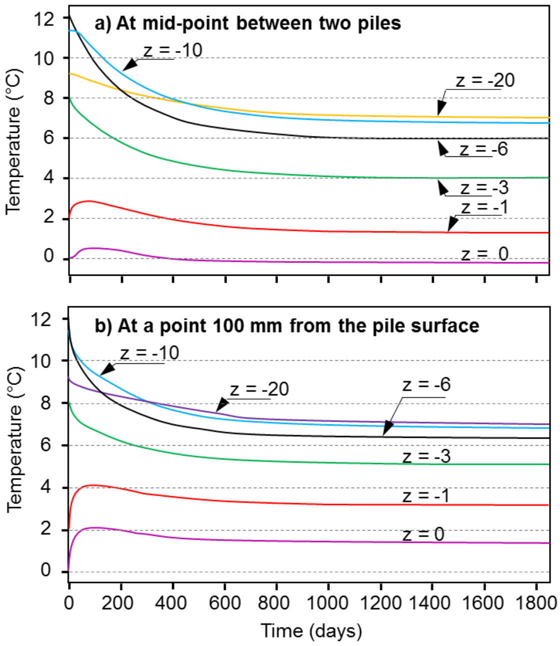


Figure 10. Ground temperature evolution after five years of heat injection at: (a) Mid-point between two piles, and (b) a point 100 mm away from the pile (3D model).

Fig. 10a shows the temperature evolution of the ground between two piles at different depths in the transient analysis when injecting heat at +7°C during a five-year analysis. As it can be seen, the steady state was reached after almost three years. However, it can be noticed that the ground at shallow depths (within the upper 1 m depth below the ice rink) is still frozen after five years of heat injection at +7°C, mainly due to the circulation of the cooling liquid in the ice rink.

Fig. 10b shows the ground temperature evolution at a point located 100 mm away from the pile border. The temperature of the ground surrounding the piles stayed at above zero temperatures when the heat injected at +7°C. Fig. 11 shows the temperature profile of the ground after one year of heat injection by the piles at +7°C.

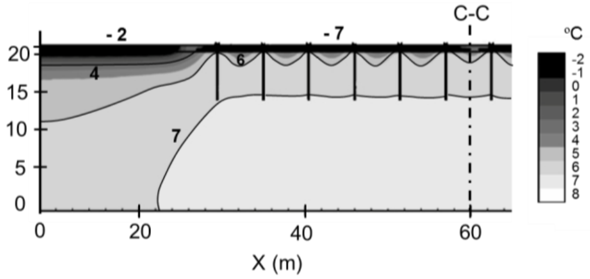


Figure 11. Ground temperature profile after one year of heat injection at +7°C (2D model).

5 CONCLUSIONS

The thawing of the frozen ground below the Myllypuro ice rink facility has been studied in detail through analytical approach and numerical simulations, and compared with in situ conditions. The primary objective of this study was to model the thawing process numerically, so that the time needed for complete thawing of the frozen ground below the ice rink can be estimated and also the ground thermal behaviour can be predicted in advance. Based on the results and insitu observations, the following conclusions can be drawn:

1. Results from the initial steady-state analysis showed that the frost depth below the ice rink was around 6.5 m – 7.0 m, which was in good agreement with the in situ measurements.

2. From the 1000-day long transient analysis that represented the thawing process from

the day when the ice rink was re-opened in December 2012,

  a. When a constant temperature boundary condition (CTBC) was applied on the pile border in the 3D model, the simulation results showed that around 400 to 450 days are required to thaw the frozen ground completely. Compared with the analytical estimation based on the influence area of a single pile, this was around 300 to 350 days less. Due to the significant discrepancies in the simulation results and analytical estimation, new simulation with constant heat flux boundary condition was done.

  b. Simulation runs with CHFBC showed that around 750 to 800 days are required for complete thawing of the frozen ground and these values were in good agreement with the analytical estimations done earlier.

3. The ground temperature profile obtained from the 2D models under CHFBC showed a good approximation to the measured in situ temperature values.

4. Once the frozen ground below the ice rink is completely thawed, a heat injection at around +7°C by the piles is sufficient to prevent the thawed ground from re-freezing.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Andersland, O.B. & Ladanyi, B. (1994). An introduction to Frozen Ground Engineering. New York, Chapman & Hall.

Cervera, C.P. (2013). Ground thermal modelling and analysis of energy pile foundations. *MSc Thesis*, Aalto University, Espoo, Finland.

Clauser, C. (2006). Geothemal Energy. In: K. Heinloth (ed), Landolt-Börnstein, Group VIII: advanced Materials and Technologies, Vol. 3: Energy Technologies, Subvol. C: Renewable Energies, Springer Verlag, Heidelberg-Berlin, 493-604.

Liu, B. & Li, D. (2012). A simple test method to measure unfrozen water content in clay water systems. Cold Regions Science and Technology, 78 (2012), 97-106.

Pirinen, P., Simola, H., Aalto, J., Kaukoranta, J.-P., Karlsson, P. & Ruuhela, R. (2012). Tilastoja suomen ilmastosta 1981-2010 [Climatological statistics of Finland 1981–2010], Technical report, Finnish Meteorological Institute. ISBN 978-951-697-766-2.

Sinnathamby, G., Gustavsson, H., Korkiala-Tanttu, L., Cervera, C. P. & Koskinen, M. (2016). Case Study: Frost heave and thaw settlement of a frozen ground. XV Panamerican Conference: Selected papers on energy geotechnics, Environmental Geotechnics (ICE), London (accepted for publication).

Sinnathamby, G., Gustavsson, H., Korkiala-Tanttu, L., Cervera, C. P. & Koskinen, M. (2015). Frost heave and thaw settlement estimation of a frozen ground. XV Panamerican Conference, Buenos Aires, Argentina.

Sinnathamby, G., Gustavsson, H., Korkiala-Tanttu, L., & Cervera, C. P. (2014). Numerical Analysis of Seasonal Heat Storage Systems of Alternative Geothermal Energy Pile Foundations. Journal of Energy Engineering (DOI: 10.1061/(ASCE)EY.1943-7897.0000236).

Sundberg, J. (1988). Thermal Properties of Soils and Rocks. Linköping, Swedish Geotechnical Institute, Report No 35.

Thode, R., & Fredlund, M. (2012). SoilVision Verification manual. SoilVision Systems Ltd. Saskatoon, Saskatchewan, Canada.

Thode, R. & Zhang, J. (2012). SVHeat 1D / 2D / 3D Geothermal Modeling Software: Theory Manual, Fredlund, M., Ed., Saskatoon, Canada: SoilVision Systems Ltd., 2012.

Thode, R. (2012). SVHeat 2D / 3D Geothermal Modeling Software: Tutorial Manual, Fredlund, M., Ed., Saskatoon, Canada: SoilVision Systems Ltd., 2012.

Thode, R. (2013). SVHeat Tutorial Manual. SoilVisions Systems Ltd.

Vähäaho, I., Koskinen, M & Uotinen, V. (2012) Suomen paksuin ikirouta. GeoFoor 38, Helsinki, Finland.