NUMERICAL SIMULATION OF GROUND THERMAL RESPONSE IN CANADIAN NO-PERMAFROST REGIONS TO CLIMATE WARMING

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ABSTRACT:

Roads, railway, and other transportation infrastructure are of vital economic, social, and political importance in all Canadian regions, particularly in Canadian no-permafrost areas. The geotechnical design and stability of these structures and many other civil engineering structures require knowledge, expertise and understanding of the thermal regime of the ground. Temperature change-induced soil freezing and thawing significantly affects the strength, bearing capacity and settlement of soils. In the present paper, the results of a modeling study to assess and predict the effect of global warming on the thermal regimes of grounds in Canadian no-permafrost regions are presented and discussed. The results show that future climate changes will significantly affect the soil thermal regimes in Canadian no-permafrost regions. The numerical tool developed, and results obtained will be useful for the geotechnical design of climate-adaptive transportation structures in Canadian no-permafrost areas.

RÉSUMÉ

Les routes, les chemins de fer et d'autres infrastructures de transport sont d'une importance économique, sociale et politique vitale dans toutes les régions du Canada, en particulier dans les régions canadiennes non-pergélisol. La conception géotechnique et la stabilité de ces structures et de nombreuses autres structures de génie civil nécessitent la compréhension du régime thermique du sol. Le cycle du gel-dégel induits par les changements de température affectent considérablement la résistance, la capacité portante et le tassement des sols. Dans cet article, les résultats d'une étude de modélisation visant à évaluer et à prédire l'effet du réchauffement climatique sur les régimes thermiques des sols dans les régions canadiennes sans pergélisol sont présentés et discutés. Les résultats montrent que le changement climatique affectera considérablement le régime thermique du sol dans les régions canadiennes non-pergélisol. L'outil numérique mis au point et les résultats obtenus seront utiles pour la conception géotechnique des structures de transport adaptées au climat dans les régions canadiennes non-pergélisol.

1 INTRODUCTION:

No-permafrost soils constitute a complex topic in frozen ground engineering. Unlike in the permafrost region, where soil remains frozen at a temperature below 0 °C continuously for more than two consecutive years, soils in the no-permafrost region are seasonally frozen including temperature below 0 °C only during the winter season (Orlando and Ladanyi 2004). The complex thermo-mechanic behavior of no-permafrost grounds raises several issues related to the design of foundations and civil engineering facilities on these soils. The freezing-thawing cycle is a thermal sequence that significantly affects the strength, heave, bearing capacity and settlement of the ground. Hence, the impact of temperature on no-permafrost soils becomes significant. However, with a rapidly changing climate, the inadequacy of earlier no-permafrost ground theories and estimated seasonal frost depths has become evidently apparent.

The prediction of climate change remains very challenging in the absence of precise estimation of how humans will behave in the future and how emissions of greenhouse gases will change (Charron 2014). Nevertheless, many research were carried out on this topic, (Government of Canada 2018) and all have raised serious warning of a negative climate change.

In Canada, the mean air temperature is expected to increase by 4 to 5 °C by the end of this century, due to global warming, which will cause a significant rise in ground temperature(Government of Canada 2018).

The impact of climate change on no-permafrost soil was studied to some extent in the past years. Studies were mainly conducted on permafrost regions. Nevertheless, no research was found in the literature being conducted on the impact of Climate change on the thermal behaviour of no-permafrost soils.

While no-permafrost soil spreads over a large portion of the Canadian territory (Slattery, et al. 2011), understanding the impact of climate change on the Canadian no-permafrost region will help geotechnical engineers optimize the design and develop safe and cost-effective alternatives to construct resilient foundation systems and infrastructure to meet the climate change requirements.

Due to the lack of research on this topic, this modeling has been undertaken to understand and assess the effect of climate change on the thermal regime of grounds located in the Canadian no-permafrost region.

2 THE STUDY AREA:

2.1 Geographical description of the study area:

The region of interest in this study is the no-permafrost area in Canada. This region extends from the Atlantic coast in the east to the pacific west coast running mainly through the whole south of Canada (Natural Resources Canada 2010). Ottawa was selected as representative site to study the conditions in the east-center of the Canadian no-permafrost region.

2.2 Climate change models in the study area in the next 100 years:

Climate Canada had established three different future climate scenarios (RCPs)(Government of Canada 2018);

- RCP8.5: high global emission scenario: This scenario indicates global average warming levels of 3.2 to 5.4°C by 2090, with a mean temperature increase of 4.9 degree by 2100.
- RCP4.5: medium global emission scenario: This scenario indicates global average warming levels of 1.7 to 3.2°C by 2090, with a mean temperature increase of 1.9 degree by 2100.
- RCP2.6: low emission global scenario: This scenario indicates global average warming levels of 0.9 to 2.3°C by 2090, with a mean temperature increase of 4 degree by 2100. (Government of Canada 2018)

Table 1 represents the projected average change in temperature and precipitations in Ottawa under three emissions scenarios (RCPs) for four future time periods: 2021-2040; 2041-2060; 2061-2080; 2081-2100 (Government of Canada 2019).

Table 1: Climate change prediction for temperature, precipitations, snow depth and annual surface wind velocity in Ottawa- (Government of Canada 2019).

Ottawa	RCPs	Annual Minimum Temperature Change (°C)	Annual Mean Temperature change (°C)	Annual Maximum Temperature change (°C)	Annual Precipitations change (%)	Annual snow depth change (%)	Annual surface wind velocity change (%)
2040	8.5	1.6	1.5	1.5	3.60%	-32.30%	-1.10%
2060	8.5	3	2.9	2.8	5.90%	-55.1	-1.70%
2080	8.5	4.6	4.4	4.3	8.60%	-67.90%	-2.40%
2100	8.5	6.1	6	5.7	10.30%	-80.20%	-2.60%

3 METHODOLOGY:

Figure 1 displays the developed approach or method for assessment of the impact of future climate on the thermal regimes of grounds in the selected Canadian no-permafrost region and the link between the different work stages performed. The method adopted comprises four main stages. The first stage deals with the establishment of the simulation tool, which includes the determination of the suitable thermal model. The second stage involves the acquisition of the actual climate conditions and the climate change predictions for the study area. The actual climate data was obtained from the Environment Canada, whereas climate change predictions were gained from the climate change interactive maps published on the Climate Change Canada website (Government of Canada, 2019). RCP

8.5 was considered in the present study. The third stage consists of the acquisition of the required geotechnical, physical and thermal data of the grounds in the study site, which were used as input data in the modeling work to be conducted. In the fourth stage of this investigation, numerical modeling and simulations of the effect of future climates on the thermal responses of the grounds in the studied site were conducted. Subsequently, the simulation results were integrated and analysed. The approach or method developed in this study can be also adopted or adapted to simulate the ground thermal regime under changing climate conditions in other no-permafrost regions in Canada or around the world. The stages/ are described in detail below.

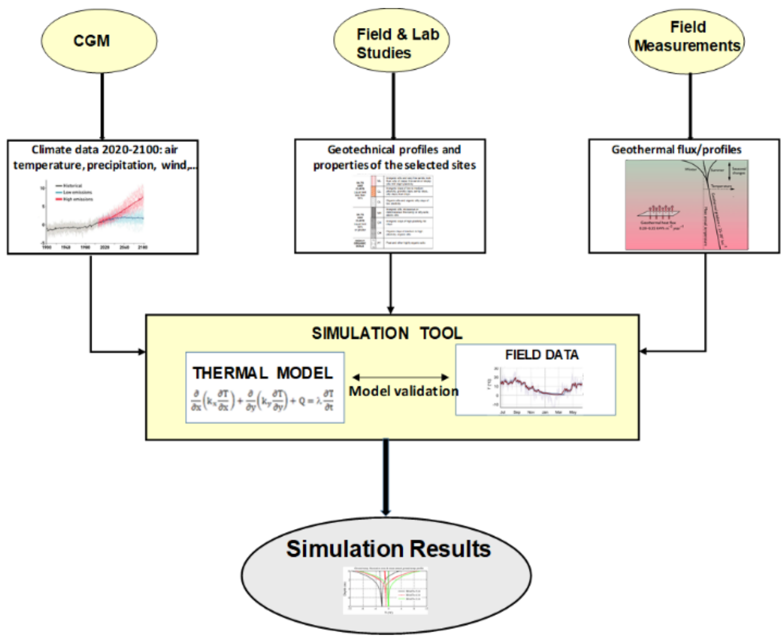


Figure 1: flow chart of the analysis

3.1 General formulations:

In most instances, conduction is the principal mode of energy transport in soils, although radiation and convection in very shallow layers also may transfer energy. Heat flow in soil can be considered analogous to heat flow in a solid to which Fourier's Law "Eq. 1" is applied:

Equation 1: Conduction equation (Flynn 2015):

$$q = -k * \left(\frac{dT}{dx}\right) \quad [1]$$

The heat flux, q, directly depends on the thermal conductivity, k, and the change of temperature, T, over a distance, x.

Equation 2 shows the differential equation that governs the formulation of 2D numerical solutions:

Equation 2: General 2D heat flow formulation (GEO-SLOPE International Ltd 2014)

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + Q = \lambda \frac{\partial T}{\partial t} \quad [2]$$

Where: T = temperature, kx = thermal conductivity in the x-direction, ky = thermal conductivity in the y-direction, Q = applied boundary flux, λ = capacity for heat storage, and t = time.

3.1.1 Steady state formulation:

The difference between the heat flux entering and leaving an elemental volume of soil at a point in time is equal to the change in the stored heat energy. At steady state, the heat flux entering and leaving the system are equal, therefore, the equation for 2D heat flow becomes "Eq. 3" :

Equation 3: 2D heat flow formulation at steady state (GEO-SLOPE International Ltd 2014)

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + Q = 0 \quad [3]$$

3.1.2 Transient analysis formulation:

In the transient analysis, the heat flux entering and leaving an elemental volume of soil at a point in time are not equal; therefore, heat energy is stored in the soil matrix. The amount of heat energy stored depends on the thermal properties of the soil. Equation 4 shows the capacity to store heat “λ” follows:

Equation 4: The capacity to store heat (GEO-SLOPE International Ltd 2014)

$$\lambda = c + L\frac{\partial w_u}{\partial T} \quad [4]$$

Where: c = volumetric heat capacity (material property), L = latent heat of water, wu = total unfrozen volumetric water content and T = temperature, Substituting for λ in the main thermal equation leads to the complete 2D heat flow differential equation “Eq:5” :

Equation 5: 2D heat flow formulation at transient analysis (GEO-SLOPE International Ltd, 2014)

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + Q = \lambda\frac{\partial T}{\partial t} = \left(c + L_w\theta\frac{\partial \theta_u}{\partial T}\right)\frac{\partial T}{\partial t} \quad [5]$$

where Q is the heat flux, kx and ky are the thermal conductivities in the x and y directions, λ the capacity for heat storage, t time. The capacity to store heat in the soil λ is composed of two parts: the volumetric heat capacity, c, that depends on whether the material is frozen or unfrozen, and L, the latent heat of fusion of the material. The latent heat calculation requires the volumetric water content, θ, the unfrozen volumetric water content, θu and L_w the latent heat of water.

3.2 The Thermal model:

The purpose of the thermal model is to simulate the ground thermal regime under different climate conditions. There are three main parts to construct a model: discretization, material properties, and boundary conditions (Flynn 2015).

3.2.1 Model geometry and discretization:

The model geometry extended 15 m laterally from the centreline, and to a depth of 20 m below the natural ground surface. The authors tried models that increased the lateral extent to 40 m, but the isotherms (temperature contours) beyond 30 m did not affect the results. The depth of the model was extended to 20 m to accurately simulate the impact of the geothermal gradient. Starting from 20 m, the ground temperature is assumed to be constant under the effect of the earth geothermal flux (Flynn 2015). The software provides a default mesh dimension. The size of the mesh influences the accuracy of the results. A square mesh of 0.2 m diameter was selected. Finer dimensions were tested; however, the software was not able to establish the analysis due to storage limitations.

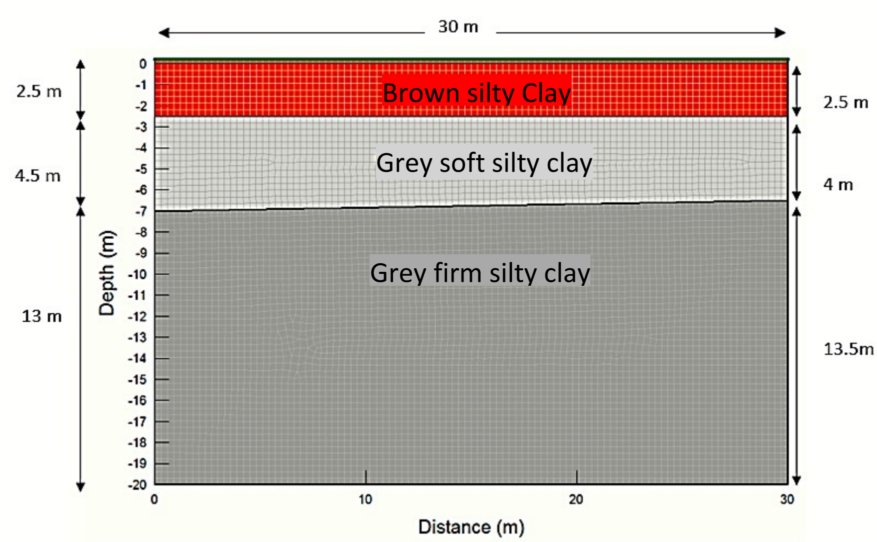


Figure 2: The geometry of the simulation model

3.2.2 Material properties:

The simulation model uses a simplified thermal approach, therefore the thermal properties required are the volumetric heat capacities (cu and cf), thermal conductivities (ku and kf), the in-situ volumetric water content (VWC), and the unfrozen volumetric water content. The material properties were retrieved from literature, for each material (Orlando and Ladanyi 2004).

Thermal properties of the Ottawa ground are summarized in the table 2:

Table 2 Material thermal properties – Toronto model - (Orlando & Ladanyi, 2004)

Soil type	ϴ (m3/m3)	Unfrozen thermal conductivity (Kj/d/m.C)	Frozen thermal conductivity (Kj/d/m.C)	Unfrozen volumetric water content (Kj/m3/C)	Frozen volumetric heat capacity (Kj/m3/C)
Brown silty clay	0.4	191.6	562.2	6556.3	4683
Grey soft silty clay	0.713	59.3	234.7	3488.7	2491.9
Grey Firm silty clay	0.7	65.5	235	3567	2547.9

3.2.3 Boundary conditions:

3.2.3.1 Steady state boundary conditions:

At steady state, the boundary condition describes the initial thermal regime of the ground. a constant temperature was applied to the top boundary and the edges of the model. It was assumed that at steady state, the ground surface temperature is equal to the average annual air temperature.(GEO-SLOPE International Ltd 2014). At the bottom extent of the model, a constant heat flux was applied to incorporate the effect of the geothermal gradient heat flux. The value of the heat flux depends on the location, but generally ranges between 0.9 and 3.3°C per 100 m. (Brown,1963).

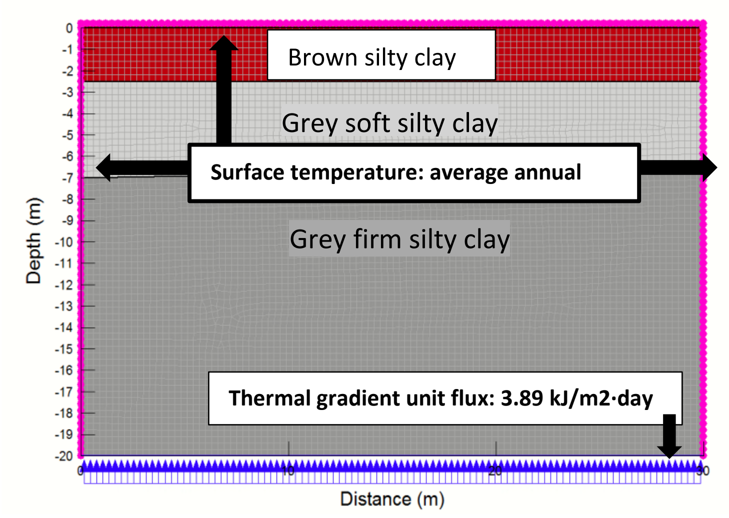


Figure 3: Steady state boundary conditions – TEMP/W model

3.2.3.2 Transient analysis boundary conditions:

The first part of the transient analyses establishes the thermal regime of the ground for the actual climate conditions. Maximum and minimum air temperatures were obtained for every day from the first day of January 2018 to the last day of December 2018 to build the first transient analysis. Five years spin up analysis were established using a cyclic climate boundary function using the actual climate data from the first day of January 2018 to the last day of December 2018. The reason behind this is to minimize the effect of the initial temperature through five cycles of the same actual climate conditions. Climate change simulations were established at the years 2040,2060, 2080 and 2100. The climate data used for each simulation are based on the actual climate data, including the climate change provided by climate change Canada website and summarized in table1. The climate values used in the simulations are modified for each year based on the climate data of 2018. For example, following the RCP8.5, the daily maximum temperature of air will increase by 1.6 in Ottawa by 2040, given that the maximum temperature in March 1st was 4 °C in 2018, the maximum daily temperature in Ottawa in March 1st will be 5.6 °C by 2040 following the RCP 8.5. The same logic applies to the rest of the climate parameters used in the analyses (Government of Canada 2018). To account for the fact that the air temperature at the surface of the model differs from the ground temperature, even at shallow depths, "n" modifying factors were required. "n" factors are empirically based coefficients used to estimate ground surface temperatures based on air temperatures. The n-factors are the ratio between thawing and freezing indices of the ground surface and the air (Johnston, 1981). They vary depending on the geographic location and surface cover. Both the freezing and thawing n factors are required in the TEMP/W analysis.

Recommended n-factors were applied based on values available from the literature. For a bare soil, the recommended thawing and freezing factors are respectively: n_{th}=1.4 and n_f=0.7 (GEO-SLOPE International Ltd 2014).

4 CLIMATE CHANGE RESULTS AND DISCUSSION:

4.1 Ground temperature profiles:

The results include ground temperature profiles and ground temperature at different depths along the sub-surface strata for December 31st and March 1st. Two days were selected to provide an understanding of the ground thermal regime at the beginning and the end of the winter season respectively. The results were limited to the winter season, since the study focused on the impact of climate change on the frost penetration depth and the frost period including the freezing-thawing cycles in the Canadian no-permafrost region.

TEMP/W provides a graphical representation of the ground temperature on each day of the analysis. The temperature contours increase from the coldest (blue) to warmest (red). The steady state analysis provides a starting point to model transient conditions. Again, it is evident that higher temperatures are at the bottom of the model due to the impact of the geothermal gradient flux as represented in figures 4.

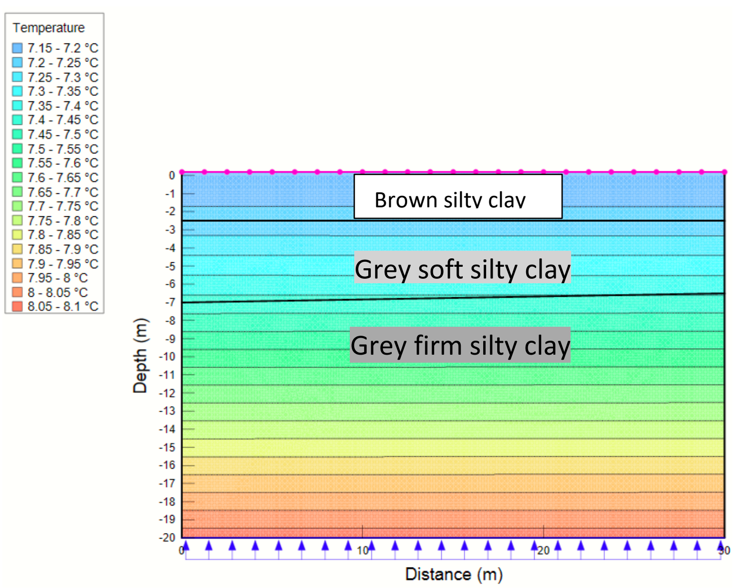
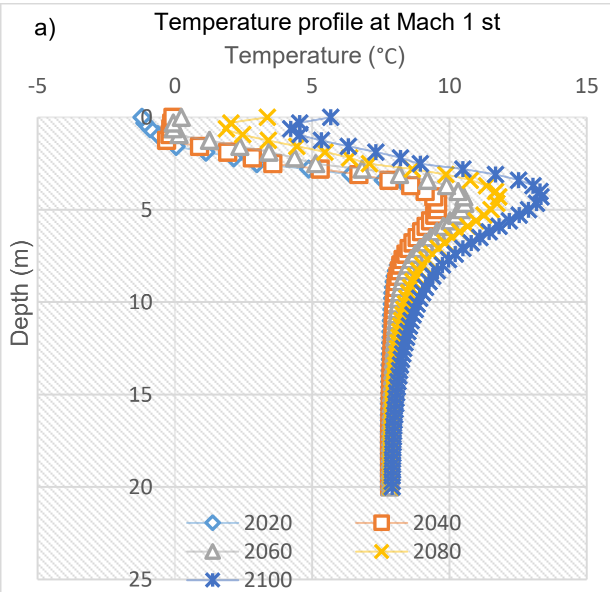


Figure 4: TEMP/W Model for Initial Conditions for the first day of the analysis for Ottawa - steady state ground temperature

Several versions of the thermal model were developed and improved through modifications of the boundary conditions, material properties, and geometry. The ground thermal regime is reported at the end of each twenty years in the period between 2020 and 2100.

Figure 5 represent the temperature profile in March 1st and December 31st respectively, of the sub-surface strata in Ottawa at 2020, 2040, 2060, 2080 and 2100.



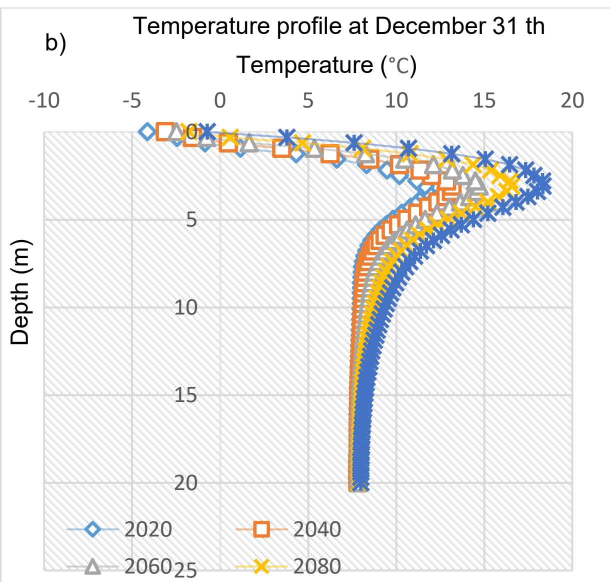


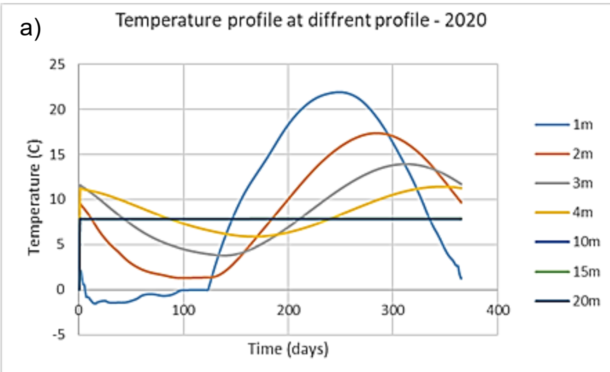
Figure 5: Ground temperature profiles at a) March 1st, b) December 31 st for 2020 – 2040 – 2060 – 2080 – 2100 – RCP8.5

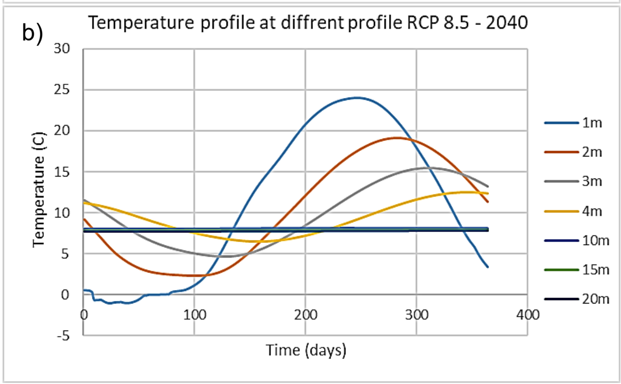
The thermal regime in the beginning and the end of the winter season are similar in shape and profile. Nevertheless, the ground at the beginning of the winter season is warmer due to the accumulation of heat in the soil matrix during the summer and the fall. At the end of the winter, the soil temperature experiences a significant drop.

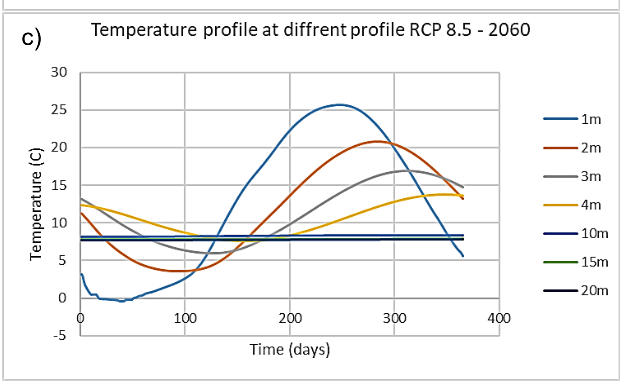
The ground temperature experiences a clear escalation from 2020 up to 2100 in both days. The rise of ground temperature is observed as a shift in the ground temperature graphs. From 2020 to 2040, the temperature rise is not clearly apparent. Global warming will not likely have a significant impact on the thermal regime of the ground in the first twenty years of the analysis due to the small rise in the air temperature by 2040. The ground temperature graphs overlap at the bottom of the model starting from a depth of 16 m due mainly to two reasons; the impact of the geo-thermal gradient on the model and the high thermal conductivity of the ground involved in the simulation model. In the presence of a ground with a high thermal conductivity, the impact of the geothermal gradient becomes significant leading to the overlapping of the thermal profiles. The ground temperature warming appears clearly starting from 2060. The impact of climate change becomes visible on the thermal regime of the ground. Ground temperature increase ranges between 0.5 °C to 2 °C at shallow depths. Again, at deeper depths, the temperature profiles for 2020, 2040 and 2060 approximately overlap due to the impact of the geothermal gradient. It was noted that at shallow depths (up to 5m) the change is more significant than at deeper depths. However, the results are only accurate for a ground that has the same material properties and geometry as the simulation model.

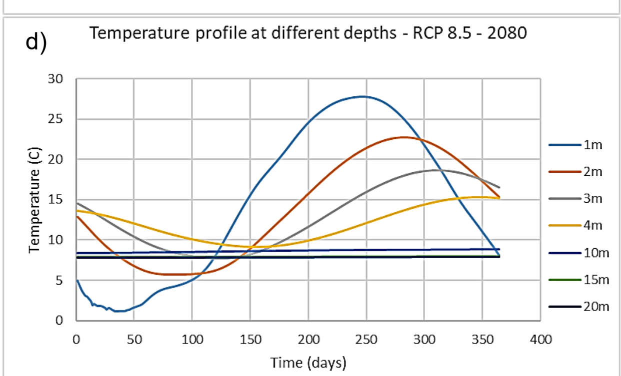
The total increase in the temperature of the ground ranges between 1°C at shallow depths to 3°C at the depth of 5m by 2100. At the top of the models, temperatures experiences larger variations due to the direct impact of climate on the soil while in deeper depths the soil equilibrium is less impacted by climate change.

In addition, it was noted that the frost penetration depth is shifted up from 1.5 m in March 1st, 2020 to 0 m in March 2100 resulting out of a complete loss of the seasonally frozen soil by 2100. The disappearance of the seasonally frozen layer indicates the absence of the freezing-thawing cycle by 2100 which will influence the consolidation behavior and the hydromechanics of the ground. The ground temperature was reported at different depths in 2020, 2040, 2060, 2080 and 2100. The temperature was reported at 1m, 2m, 3m, 4m, 15 m and 20m below the ground surface. These depths were selected to visualize the variation of the soil temperature due to the impact of climate change at shallow and deep depths. Figures 6 summarize the ground temperature at 1m, 2m, 3m, 4m, 15 m and 20 m in Ottawa in 2020, 2040, 2060, 2080 and 2100.









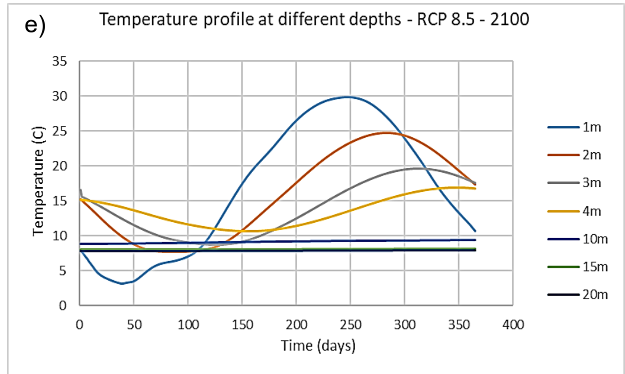


Figure 6: Temperature profile at different depths - RCP 8.5 at a) 2020, b) 2040, c) 2060, d) 2080, e) 2100 - Ottawa

The temperature fluctuations of the ground are heavily impacted by the air temperature at shallow depths. Yearly periodic temperature cycles were observed at 1m, 2m, 3m and 4m depth. Ground temperature fluctuates depending on the seasons creating a frost period where the ground freezes. The length of the frost period depends mainly on the climate conditions and the ground thermal properties. In the actual climate conditions, Ottawa experiences a frost period lasting approximately for 156 days. Due to climate change the length of the frost period gradually decreased from 2020 up to 2100. It is observed that there will be a loss of approximately 40% of the frost period by 2060 in Ottawa. The frost period will experience a continuous loss up to 2100 where it totally disappears.

5 CONCLUSION

The modeling carried out in this paper established future simulations of the ground thermal regime in response to global warming.
The authors framed the study to Ottawa and considered only climate change scenario 8.5. The simulation model is divided into four periods of time, each period lasts for 20 years, starting from 2020 up to 2100. Results were reported at 2020, 2040, 2060, 2080 and 2100.
The study has come up with the following conclusions:

1) - The simulation results showed a gradual loss in the frost penetration depth**,** in Ottawa due to global warming.

2) - The mean average ground temperature would be much higher and will likely increase by 3 °C in the center of the Canadian no-permafrost region

depending on the soil composition and climate conditions.

3) -The frost period duration will be shorter due to global warming in the center of the Canadian no-permafrost region and will totally vanish in Ottawa by 2100.

4) - The impact of climate change on the thermal regime of the ground is non-linear, this implies that substantial changes could follow in a short timeframe and climate change will need at least 40 years to mobilize a significant change in the thermal behaviour of the ground.

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