Design of Horizontal Ground Heat Exchangers in Sub-Arctic Conditions – Sensitivity to Undisturbed Ground Temperatures

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Abstract. Application of ground source heat pumps (GSHPs) in extreme cold climates can be challenging due to the long heating season even with heat pumps designed and marketed for colder climates. One challenge (of several) is design of the ground heat exchanger under conditions where the desired minimum heat pump entering fluid temperature (EFT) is close to the undisturbed ground temperature (UGT). Furthermore, ground heat exchanger (GHE) models used for design purposes and/or energy calculation purposes don't usually incorporate freezing and thawing of the soil. This is the case whether the freezing/thawing is induced by surface conditions or by heat transfer between the ground heat exchanger and the surrounding soil. A recently developed model [1] implemented in a simulation-based ground heat exchanger design tool [2] incorporates the effect of surface-condition-induced freezing/thawing when calculating a 2nd-order harmonic approximation for the undisturbed ground temperature. This paper examines the suitability of this harmonic model in GHE design applications by comparing the predicted GHE design to the actual design of a GHE at the Cold Climate Housing Research Center (CCHRC) in Fairbanks, Alaska. Field measurements of UGT and GHE performance are used to examine the limitations of the harmonic model.

Keywords: Ground-source heat pumps, horizontal ground heat exchangers.

1 Introduction

The design of ground heat exchangers, particularly horizontal ground heat exchangers, is sensitive to the undisturbed ground temperatures (UGT). For shallow horizontal ground heat exchangers, the time-varying aspect of the UGT may be of importance. Time-varying UGT have generally been estimated with some variation of the Fourier [3] model. Kelvin [4] used a 2nd order model to represent ground temperatures in Edinburgh. The ASHRAE Handbook series gives a 1st order model, with annual average temperatures and amplitudes given on small hard-to-read maps that cover North America. These maps are adapted from research done in the 1920s [5] and 1950s [6].

An improved method [1,7,8] that provides 2nd order harmonic model coefficients for over 4000 locations worldwide relies on a numerical model coupled with typical meteorological year-type weather data to provide a temperature data set for each location that is, in turn, used to tune the coefficients of the 2nd order harmonic model. The numerical model accounts for freezing in the ground, but relies on a heuristic model [1] to estimate the accumulation of snow.

It should be emphasized here that the purpose of the 2nd order harmonic model and accompanying worldwide data set is to provide reasonable estimates of UGT to support design of ground heat exchangers and calculation of heating loads. The procedure for determining the model coefficients for each location necessarily made a number of approximations in addition to the heuristic model for snow accumulation. E.g., fixed values of soil thermal diffusivity were used; the surface evapotranspiration model was limited to short grass and tall grass conditions; and likely most importantly, the weather was assumed to be a repeated typical meteorological type year. The model is intended for use in situations where detailed ground temperature measurements are not available.

Grundmann [9] implemented the improved UGT model in the GHE design software GLHEPRO [2] along with a database of coefficients. The program also includes a model of Slinky-type horizontal GHE, developed by Xiong, et al. [10]. This model is based on superposition of ring-sources and is implemented to support sizing of the Slinky-type GHE.

At roughly the same time as these new models were being developed and implemented, the Cold Climate Housing Research Center (CCHRC) installed, instrumented, operated, and monitored a ground-source heat pump system utilizing horizontal Slinky-type GHE in Fairbanks, Alaska.

This gives the opportunity to check the applicability of the UGT and Slinky-type GHE sizing capability against real-world data in a subarctic climate. Therefore, the purpose of this paper is to compare predictions of undisturbed ground temperature and ground heat exchanger design results to actual field measurements and system operation.

2 Facility and Field Measurements

CCHRC's Research and Testing Facility (RTF) is 2,044 m^2 of office and lab space. The building has 3 distinct heating areas, which are defined by their heat delivery mechanism. The 464 m^2 office section is heated with the ground source heat pump [11] and a supplementary wood fired masonry stove. Heat in the office section is distributed via an in-floor hydronic system embedded in concrete; it is zoned using 9 thermo-statically-controlled valves. The office section has a 17.6 kW heating design load.

The soils around the RTF have been studied extensively and that information was used to inform the GHE design. The soil underlying the site is moist silt and either degraded or degrading permafrost. Boreholes drilled on the site in 2006 prior to the construction of the RTF found the site underlain with sloping permafrost. The top of the layer started at 3 m on the south side of the building near the undisturbed vegetation and sloped down to 9.1 m on the north side where the native vegetation had been cleared. Data collected under the east end of the RTF since 2006 shows that the permafrost table has further degraded by an additional 0.6 m. A test borehole northwest of the RTF in 2012, prior to installing the GHE, did not find permafrost within 9.1 m of the surface. In addition to changing permafrost, the ground water levels across the site are changing. It is estimated that the ground water has risen 1.5 m since 2006; most of that rise is since 2013. The proximity of permafrost with ground temperatures close to freezing and the changes in ground water are having an impact on the GHE.

The heat pump is a commercially available residential unit with nominal capacity of 21 kW. It was sized entirely based on the heating load. The heat pump heats a 303-liter buffer tank of water to a temperature determined by the outdoor set point curve. The minimum temperature set point for the buffer tank is 26.7°C and the maximum is 42.8°C. The GHE side of the heat pump is charged with a 20% methanol, 80% water mixture. The building hydronic side of the heat pump is charged with water.

The horizontal GHE was designed based on the technology available in Fairbanks in 2012. Since directional drilling was not an option and deep vertical wells would have run into cold, frozen bedrock, horizontal "slinky" coils were installed. Six 30.5 m long by 1 m wide slinky coils with a 0.5 m pitch were installed 1.8 m apart. Overall, 1,463 lineal m of 1.9 cm HDPE was installed at 2.7m depth to create the in-ground heat exchanger.

The GHE size and depth were determined by knowledge of past installations in the area, in conjunction with ground thermal conductivity test data, and information from a finite element model. The ground heat exchanger was designed by the local GSHP installer using his modified version of IGSHPA methodology [12, 13]. Due to the underlying permafrost, he assumed 0°C ground temperature and a minimum -3.3°C entering fluid temperature. The tested thermal conductivity was lower than the typical estimates in the Fairbanks area so the FEM model was used to support increasing coil spacing from the usual 0.9 m to 1.8 m.

The heat pump system is monitored in order to evaluate how the heat pump affects the soils around the GHE and also how the changing entering fluid temperatures affect the heat pump efficiency. It is expected that the large imbalance of heat extraction without enough thermal recharge will depress the temperatures in the GHE over time. The CCHRC installation was designed to investigate this and to determine if the GHE temperatures stabilize over time. Temperature data is being collected throughout the GHE, as well as outside the GHE. Five vertical thermistor strings measure temperatures at depths up to 3.7 or 4.1 m. Three vertical thermistor strings measure temperatures inside GHE; two strings are installed outside of the GHE. All of these strings record soil temperatures on an hourly basis. The manifold for this system is located inside the building and the fluid temperature from each slinky coil is tracked on an hourly basis. The energy from the GHE, to the buffer tank, and to the building is also monitored, as is the electrical use of the system. Figure 1 shows the locations for the vertical thermistor strings. The system came online in October 2013 and our data collection system became fully operational a year later.

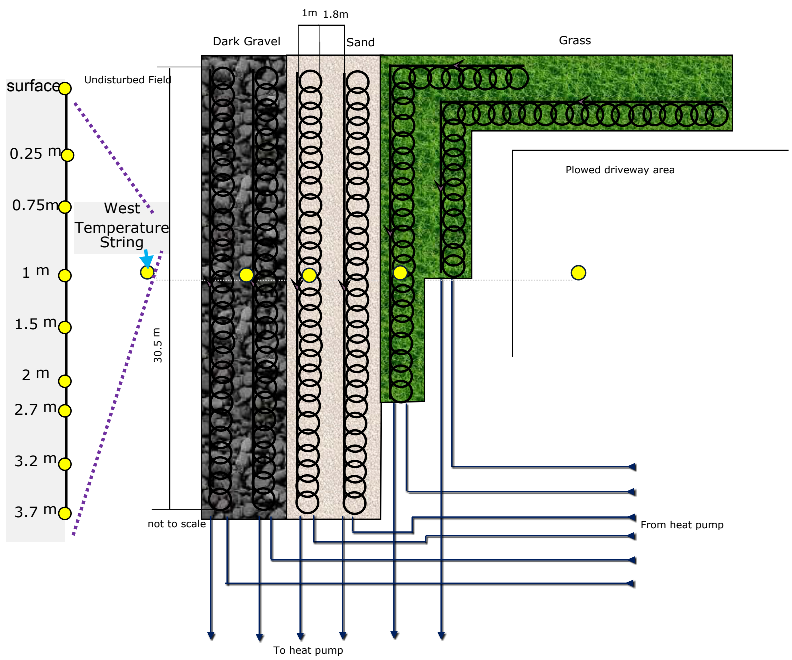

Fig. 1. Ground heat exchanger layout with vertical temperature sensor string locations marked.

3 Ground Temperature Measurements and Model Results

As will be shown in the Section 4, the design of the ground heat exchanger is very sensitive to the undisturbed ground temperatures. An initial comparison can be made for the depth of the ground heat exchanger, 2.7 m, as shown in Figure 2. The measured UGT covering the period from 10 October 2014 to 2 June 2017 come from the vertical temperature string 4 m west of the west-most slinky GHE. Two model curves are plotted, representing short grass (Model-SG) and tall grass (Model-TG) conditions. The temperature string is under short grass cover. The first and most obvious difference is that, even with tuning of the coefficients using a numerical model that considered freezing and snow accumulation, the harmonic models don't match the shape very well, with maximum errors of about 3°C.

This is because, even with the tuning, the harmonic model itself represents a pure heat conduction solution, with 2nd order harmonic boundary conditions. The harmonic model's ability to account for freezing at the surface is very limited.

Furthermore, the model relies on standard boundary conditions (e.g. "short grass") and typical meteorological data, so even the annual average temperature cannot be predicted perfectly at every location. The model has an average temperature of 2.4°C for every year. The measured average temperature for 2015 (excluding a 40-day period when the temperature sensor failed) was 3.2°C. The measured average temperature for 2016 (excluding an 8-day period when the temperature sensor failed) was 3.1°C.

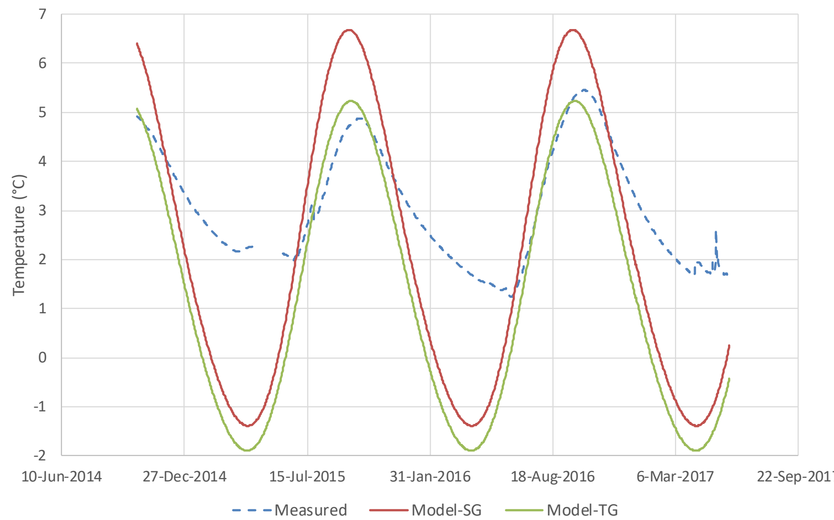

Fig. 2. Undisturbed ground temperatures at 2.7 m depth – measured and modeled.

Figure 3 shows for 1 m depth the measured temperatures, the 2nd order harmonic model-predicted temperatures ("Model-SG"), and the temperatures ("Numerical UGT") predicted by the numerical model [1,7] that were used to fit coefficients for the 2nd order harmonic model. The effect of freezing can be clearly seen in the numerical model, but there is still significant deviation from the measured data. A likely explanation is that the heuristic snowfall model underpredicted the amount of snow cover; both winters were heavy snowfall years with early snowfall that insulated the ground. This is consistent with measurements from a second site, 1 km away, which shows that the ground temperatures during 2014-2016 were somewhat warmer than 2008-2015. From 2008-2013, annual minimum temperatures at 2 m depth were 0.1-0.2°C. Then from 2014-2017, the temperatures rose: 0.34, 0.42, 0.63, 0.84°C.[14]

Keeping in mind that the harmonic model is intended to be globally-applicable and it is intended to be applied in designs where some oversizing of a GHE is acceptable, and that the model has been shown to be more accurate than similar previous models, perhaps it may be considered adequate. Nevertheless, in the authors' opinion, it would be desirable to have a better, but still simplified, design model that better included freezing and snowfall effects.

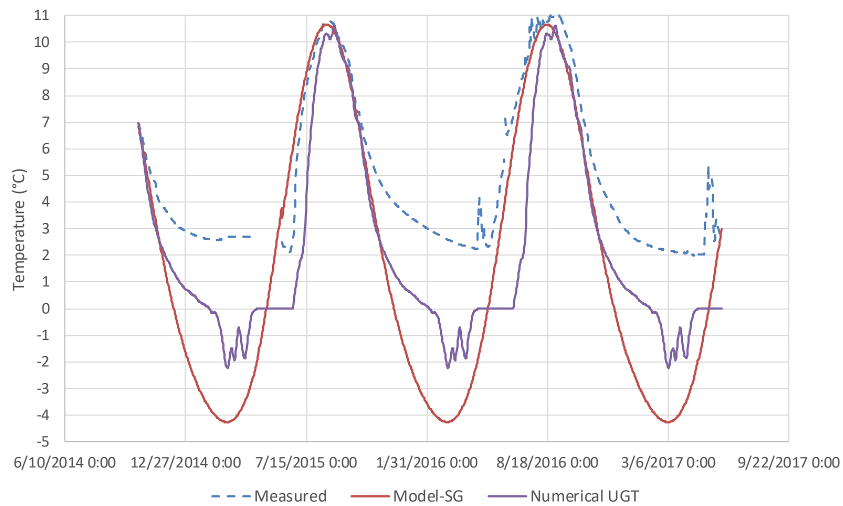

Fig. 3. Undisturbed ground temperatures at 1 m depth – measured and modeled with both harmonic model and numerical model.

In order to investigate the advantage of a better model when applied to GHE design, a surrogate location was sought that would better match the measured UGT at 2.7 m depth. This was accomplished by fitting the measured data to the harmonic model, which gave a mean annual surface temperature of 3.1°C and amplitude of 4.6°C. Then, all other locations worldwide were sorted by how closely they matched these values. Specifically, a goodness-of-fit parameter was calculated as a weighted sum of the errors squared – the annual temperature was assigned a weight of 2/3 and the first-order amplitude was assigned a weight of 1/3. The selected surrogate location was St. Paul Island, Alaska – one of the Pribilof Islands – and it has a mean annual temperature of 2.9°C and a first-order amplitude of 4.4°C. The model-predicted UGTs at 2.7 m depth for both Fairbanks and St. Paul Island are compared to the measured UGTs in Figure 4. At least at 2.7 m depth, the St. Paul Island UGTs are a much better representation of the measured UGTs in Fairbanks.

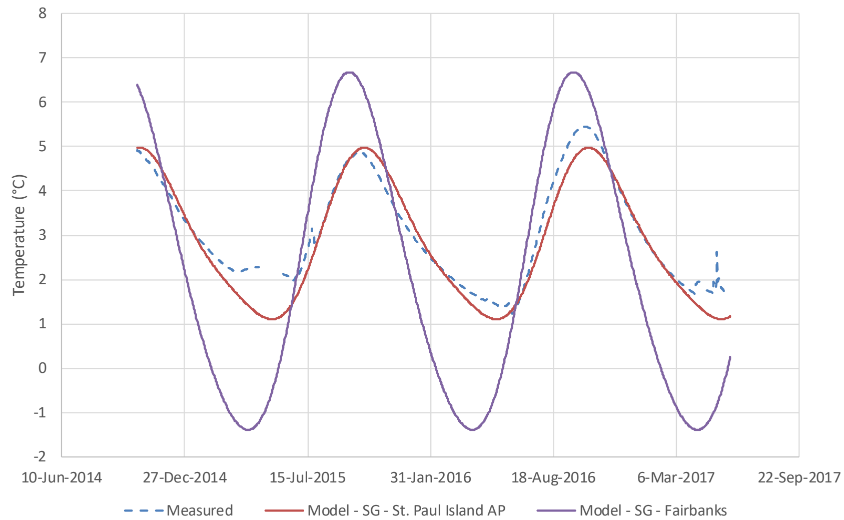

Fig. 4. Undisturbed ground temperatures at 2.7 m depth – measured and harmonic model results for both Fairbanks and St. Paul Island.

4 Ground Heat Exchanger Design

Ground heat exchanger design methodologies may be broadly grouped into two categories: simplified analytical approximations and simulation-based design tools. The first category consists of methods where an analytical approximation to the line-source solution has been algebraically solved to give a design length. The second category consists of methods where the GHE size is treated as an input to a simulation; the size is then automatically adjusted so that the user-specified minimum or maximum heat pump entering fluid temperature is reached, but not exceeded.

GLHEPro, is a simulation-based design tool, and, specifically, a simulation of Slinky-type heat exchangers is made and the size of the ground heat exchanger is then adjusted to meet the minimum heat pump EFT. The simulation can account for most of the features of the installation, but not all. As shown in Figure 1, two of the trenches take a right turn, so we expect that there will be less thermal interference in the facility than predicted by the simulation. Also, there are three different surface covers; only two of the trenches are covered by grass. Garber-Slaght and Peterson [11] discuss the effect of the surface cover on the returning GHE temperatures. At the beginning of the 2015 heating season, the gravel-covered return temperatures were about 1°C higher than the grass-covered return temperatures and about 0.5°C warmer than the sand-covered return temperatures. But these differences were reduced over the winter, so that by the end, all return temperatures were within a 0.3°C band.

An initial comparison might be made by using the GLHEPro monthly/monthly peak simulation [15] to estimate the average heat pump EFT at month end and the minimum monthly heat pump EFT. These temperatures are plotted along with measured hourly heat pump EFT, using both Fairbanks and St. Paul Island to provide the UGTs for the simulation in Fig. 5. As might be expected, using the St. Paul Island UGTs gives a much better match to the actual measured heat pump EFT. Even using the St. Paul Island UGTs, other deviations between the hourly measurements and the monthly/monthly minimum estimates are caused by a number of factors: heat transfer differing from pure conduction due to freezing around the tube and water movement; limitations of the hybrid time step representation [15]; use of a mixed monthly load profile in GLHEPro; differences in geometry; inhomogeneity in the soil; and, other factors. The degree to which this affects the predicted GHE size will be examined next.

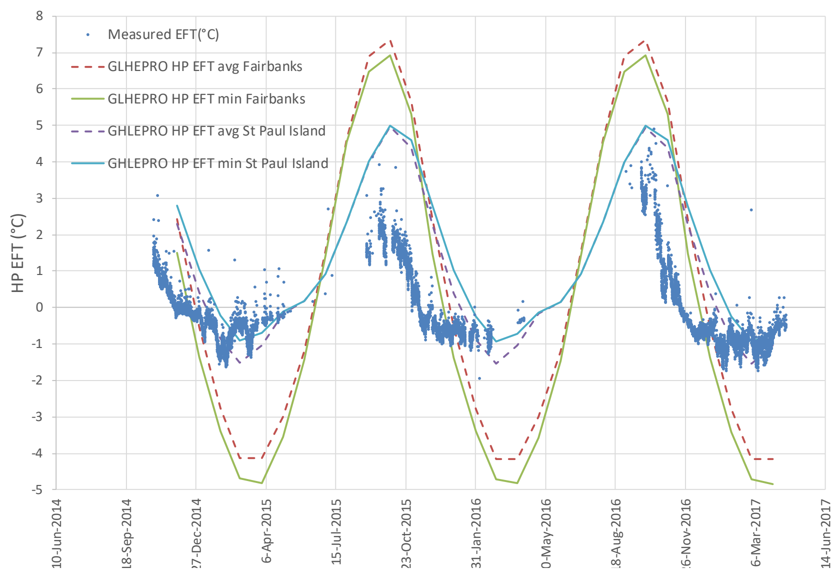

Fig. 5. Measured and simulation-predicted heat pump EFT using UGTs for both Fairbanks and St. Paul Island.

In general, the GHE size becomes more sensitive to all parameters as the required minimum heat pump EFT approaches the UGT. This is illustrated in Fig. 6, where the required GHE size (given as the trench length for each of the six trenches) is plotted as a function of the user-specified minimum heat pump EFT. The GHE has been specified as consisting of six Slinky heat exchangers with the pitch, spacing between trenches, depth, flow rate, etc. all set by the user. The trench length and amount of pipe are then adjusted automatically to meet the minimum heat pump EFT.

Four curves are given, representing four different UGT conditions – Fairbanks and St. Paul Island, as already discussed, and two fixed temperatures (3.15°C, representing the measured annual average UGT at the GHE depth, and 2°C representing an approximate average value of measured UGT at the GHE depth during the heating season.) In addition, two points are shown. The first represents the conditions during the 2014-

2017 period of measurements, where the minimum heat pump EFT is about -1.7°C and the actual trench length is 30.5 m. The second point represents the contractor's design minimum heat pump EFT of -3.3°C and the actual trench length.

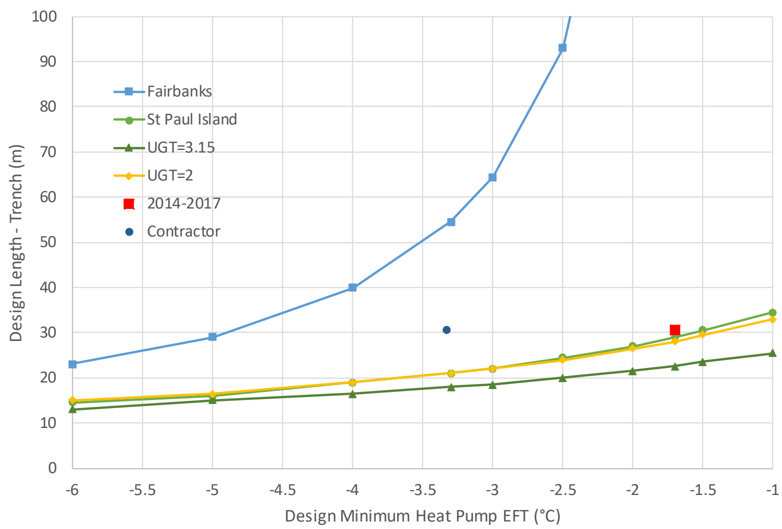

Fig. 6. Sensitivity of GHE design to UGT.

To return to the importance of the UGTs used in the design, Figure 4 shows that the 2nd order harmonic model, using parameters for Fairbanks, underpredicts the minimum annual ground temperature at the GHE depth by a little less than 3°C. Yet, as can be seen in Fig. 6, this has a substantial effect on the required GHE size, and, in practice, the design engineer does not have the luxury of multiple years of measured data on site when the system is being designed. At the minimum heat pump EFT used by the contractor (-3.3°C), the GHE sized with the Fairbanks data would be 2.6 times larger than the one sized with the St. Paul Island data. So, yes, the 3°C difference is very significant under these conditions; specifically, the small difference between the minimum UGT and the design heat pump EFT.

We may also compare the actual performance for 2014-2017. During these years, the minimum heat pump EFT actually reached was -1.7°C and the actual trench length is 30.5 m. The sizes predicted by the St. Paul Island data and constant 2°C UGT are slightly smaller than actual (5% and 8% respectively); and the size predicted by the constant 3.15°C UGT – the annual measured average temperature - is 26% lower. Since using the average annual measured UGT underpredicts the size, it suggests that accounting for the annual variation in UGT is important.

One other observation is related to the fact that the Xiong, et al.[10] model used by GLHEPro does not account for freezing around the piping. It seems likely that this should be important, but it is not clearly evident from the results observed here. Looking at Fig. 5, it seems that each heating season, the measured temperatures decrease sooner than GLHEPRO predicts, and then flattens out around heat pump EFTs of -1°C. It is possible that the measured decrease in temperature is partly due to residual ice around the tubes and that the flattening-out observed is due to further freezing around the tube. But this is somewhat speculative.

5 Conclusions and Recommendations

Though an improvement over what was previously available, the 2nd order harmonic model of undisturbed ground temperatures [1,7,8] implemented in GLHEPRO under-predicts the UGT in Fairbanks' sub-arctic climate by around 3°C, leading to an over-prediction of required horizontal ground heat exchanger size. GHE size is shown to be increasingly sensitive as design EFT approaches the UGT.

The form of the 2nd order harmonic model has limited applicability to sub-arctic conditions with a substantial amount of annual freezing and thawing at the ground's surface. Furthermore, examination of the numeric model results used to fit the 2nd order harmonic model constants suggests that the heuristic snow cover model needs improvement. Development of the heuristic snow cover model [1] was hampered by a lack of a precipitation data in the typical meteorological year type weather files used to generate the worldwide database. Therefore, a possible improvement could be along the lines of:

- Investigate alternative sources that provide global precipitation data, with as fine a time resolution as possible. E.g. monthly average precipitation data should be better than annual average data.
- Develop an improved, but probably still heuristic, model of snow cover and implement this in the numerical procedure used to develop the tuning data. For the 2nd order harmonic model, the tuning data are daily temperatures at four depths.
- Develop an alternative to the harmonic model that is still simple enough for widespread design applications, but which provides a better fit to the numerical model.

Finally, the Xiong, et al. [10] model gave quite reasonable results – predicted size within 5% of actual size when the temperature inputs were adjusted to better match measurements at the site. However, the impracticality of making long-term field measurements at multiple depths for most design applications reinforces the need for improved UGT models.

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