A novel freeze protection strategy for shallow buried sewer pipes: temperature modelling and field investigation

Youen Pericault, Mikael Risberg, Mattias Vesterlund, Maria Viklander and Annelie Hedström

ABSTRACT

The burial of sewer and water pipes below the maximum ground frost depth can be very costly and laborious in regions with cold winters. If a freeze protection measure is applied, the utility lines can be installed in a shallower trench to reduce the excavation needs. One freeze protection measure, so called heat tracing, consists of supplying heat along the pipes. In this work, the use of 4th generation district heating as a heat tracing solution was investigated at a pilot site in Kiruna, Sweden. The influence of the system on sewer and water pipe temperatures was studied at a snow-free and snow-covered cross section. To this end, five heat tracing temperatures were tested and the corresponding sewer and water pipe temperatures were measured. The field experiment was also simulated with a two dimensional finite volume model. The study showed that, under the climatic conditions of the experiment, a heat tracing temperature of 25 °C allowed prevention of freezing of the pipes while keeping drinking water pipes in a safe temperature range at both cross sections. The other main result was that the developed finite volume model of the sections showed a good fitting to the experimental data.

Key words | district heating, heat tracing, low temperature, pipe insulation, temperature modelling, utilidor

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INTRODUCTION

The traditional way to protect sewer and water lines from freezing in the winter is to bury them below the maximum ground frost depth. However, a shallower installation is sometimes preferred in order to reduce the excavation and backfilling costs. This is usually done if the frost penetration is severe (typically more than 2 metres) or if the bedrock is situated above the design frost depth. Such practice is reported in continental sub-arctic (McFadden 1990) and polar climates (Hazen *et al.* 1990) but also in rocky areas affected by a wet continental climate (Gunderson 1978; Coutermarsh & Carbee 1998). Avoiding the deep burial of sewer and water pipes gives the opportunity to place these utilities in a common trench with district heating, electricity and telecommunication lines. In this way, expenses during construction and maintenance works can be shared between the utility providers. Another advantage of shallow buried sewer pipes is the possible reduction of groundwater infiltration, since the pipes are less likely to be under the groundwater table. On the other hand, pipes installed above the ground frost depth have the disadvantages of being more affected by traffic loads and requiring a freeze protection solution. The latter represents extra costs, energy use and emissions during the manufacturing and, possibly, also during the operation of the system.

One measure to prevent freezing is to properly insulate the sewer and water pipes either individually (Coutermarsh & Carbee 1998; Bai & Wang 2013) or together in a hollow (Kennedy *et al.* 1988) or sand-filled (McFadden 1990) utility corridor (utilidor). In pipe network sections influenced by a continuous flow, insulated pipes are usually sufficient to prevent freezing. However, sections with intermittent flow patterns such as dead ends, house connections and low density areas are subjected to freezing even with insulation. In this case, several solutions are available to provide heat to

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the pipes. A background flow can be maintained in the water and sewer pipes using bleeding valves or by sending let-run notices to the residents (Raymond *et al.* 1999). Recirculation systems can also be used to ensure a continuous flow in water pipes. This might provide heat to the sewer if a utilidor is used (Schubert *et al.* 2013). Heat-tracing is another widely used solution that consists of supplying heat along the pipes with an electrical tape or with hot fluid circulation pipes. The freeze protection strategy studied in this paper is a heat-traced utilidor currently tested in a new residential area of Kiruna in northern Sweden. The sewer and water lines are installed in an expanded polystyrene (EPS) utilidor at a depth of approximately 1 metre, whereas the frost penetration can reach 2.5 metres in this area. The system is heat traced with pipes of warm water diverted from the 4th generation district heating system of the neighbourhood.

To our knowledge, such a solution has not been implemented in the past, probably because 4th generation district heating is an emerging technology. Related examples are reported in the literature though. Kennedy *et al.* (1988) studied a heat traced utilidor in central Alaska to verify its ability to prevent freezing and to evaluate the thermal impact on the surrounding soil. Haviland (1983) compared different utilidor designs in terms of energy efficiency and economics, based on calculations of the equivalent thermal resistance of the system. However, no study has been found in the literature concerning the influence of utilidor heat tracing on sewer and water pipe temperatures. These temperatures are of importance, since they can affect wastewater treatment efficiency and drinking water quality. For example, high drinking water temperature may negatively affect important performance indicators such as 'customers' complaints' and 'violations of water quality analysis' (due to enhanced bacteria growth) proposed by Marques & Monteiro (2001). The utilidor in Kiruna has snow-covered sections that require less heat for frost prevention than its critical snow-free sections. During the first year of operation, this sometimes resulted in drinking water temperatures above the local regulation threshold for water quality of 20 °C. Cold climate engineering manuals (Smith 1996; Freitag & McFadden 1997) focus on freeze protection in heat-traced utilidors but provide little guidance to limit drinking water temperature and estimate the impact of these systems on sewage temperature.

The current research project concerning the heat tracing solution installed in Kiruna aims at: (a) proposing operation practices and, if needed, re-design of the system to prevent freezing of the utility lines while ensuring healthy and comfortable drinking water temperatures; (b) estimating the district heat consumption of the system and its impact on sewage temperature. The main objective of this paper is to compare the thermal behaviour of a snow-free and a snow-covered section of the utilidor of Kiruna under given climatic conditions. The second objective is to assess the relevance of two dimensional (2D) finite volume modelling for future thermal characterizations of the system's cross sections. To this end, two cross sections were studied experimentally with temperature measurements during late winter 2016. A finite volume simulation of the experiment was conducted using the ANSYS CFX software, and results were compared with experimental data. The case study, experimental setup, experimental protocol and finite volume model of the study are presented in the Methods section of this paper. The Results and discussion section mainly provides a comparative analysis of the cross sections' thermal behaviours and presents the corresponding implications for the regulation of the system. The methodology and main findings are then summarized in the Conclusion section.

METHODS

Case study

The city of Kiruna has a population of 18,000 and is located in Northern Sweden. The climate is continental subarctic with short summers and long, cold winters. The air temperatures are usually negative from October to April, with average daily temperatures of −17 °C during January and February (SMHI 2014a). On average, snow cover lasts from mid-October to mid-May and reaches a maximum of 80 cm during this period (SMHI 2014b). Major parts of Kiruna, including its city centre, will be relocated before 2030 because of mining activities, which are the cause of land subsidence. The heat density will be necessarily reduced in the new city, especially in residential areas composed of energy efficient single family houses. To adapt its district heating network to the reduced heat demand, the utility company of the city has implemented an innovative distribution system for the expansion of Tuolluvaara residential area. The pilot project consists of eight plots connected to a 4th generation district heating system. This technology greatly reduces the network heat losses in comparison with the current district heating generation and is well suited for low heat density areas (Lund *et al.* 2014). Moreover, the 4th generation district heating pipes are placed together with the sewer and water pipes in a single shallow trench to reduce their installation costs and improve the competitiveness of district heating in the area.

With lower operating temperatures and small flexible pipes, 4th generation district heating also offers new possibilities for conveniently heat tracing water and sewer pipes. Therefore, the sewer and water pipes were placed in a shallow utilidor (~1 metre below grade), well above the design frost depth of 2.5 metres, at the pilot site. The utilidor in EPS is freeze protected with part of the district heating return water (between 30 and 35 °C) circulating in a pipe. This heat tracing pipe is depicted in orange on the aerial view presented in Figure 1 (the full colour version of this figure is available in the online version of this paper, at http://dx.doi.org/10.2166/wst.2017.174). The district heating return water is pumped from the district heating house station to the different properties, where it is re-injected into the district heating return pipe. At each house connection, the heat tracing flow is controlled by a thermostatic valve regulated according to the heat tracing fluid temperature. The sewer, water and heat tracing pipes have a constant spacing along the EPS utilidor. This can be seen in the picture of the utilidor's construction in Pericault *et al.* (2016). The 4th generation district heating supply and return pipes are insulated and placed in the same trench as the water-sewer utilidor (~0.7 metre below grade), as shown in Figure 2.

Experimental method

Two cross sections of the system utilidor and surrounding soil and snow cover were analysed at the study site. Their locations are indicated in Figure 1. Cross section 1 is situated under the lawn of habitation A1 (Figure 1) and is covered by snow during winter. Cross section 2 is under the carport of the same property (Figure 1); it is free of snow during winter and exposed to outdoor air temperatures. The geometries of cross sections 1 and 2 are presented in Figure 2. Due to practical reasons during the construction, the cross sections have different geometries. As seen in Figure 2, the district heating lines are situated right above the water-sewer utilidor at cross section 1, but are located to the right of the sewer-water utilidor at cross section 2. The heat tracing water is not re-injected into the district heating return pipe directly at habitation A1 but at habitation A2. For that reason, the heat tracing pipe is doing a loop in the A1 house connection. Cross section 2 has consequently two heat tracing pipes (supply and return of the loop).

The thermal behaviour of the utilidor at cross sections 1 and 2 was investigated during an experimental test period, from 2016-02-17 to 2016-02-21. The average air temperature during the week preceding the experiment was −3.7 °C. During the experiment, this average was of −4.1 °C.

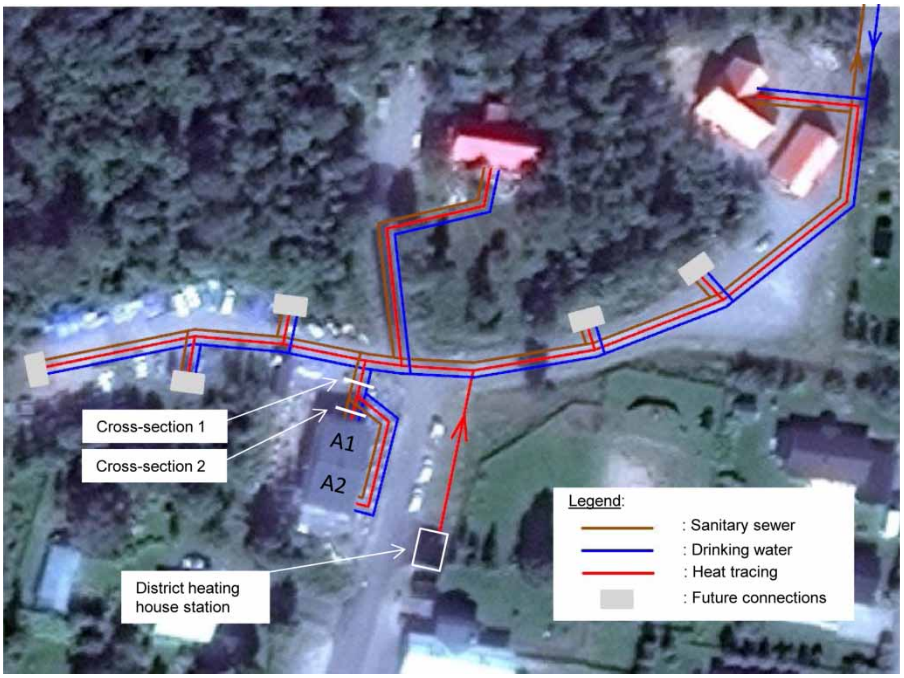

Figure 1 | Aerial view over the pilot site. The district heating pipes are not visualised here. The full colour version of this figure is available in the online version of this paper, at http://dx.doi.org/10.2166/wst.2017.174.

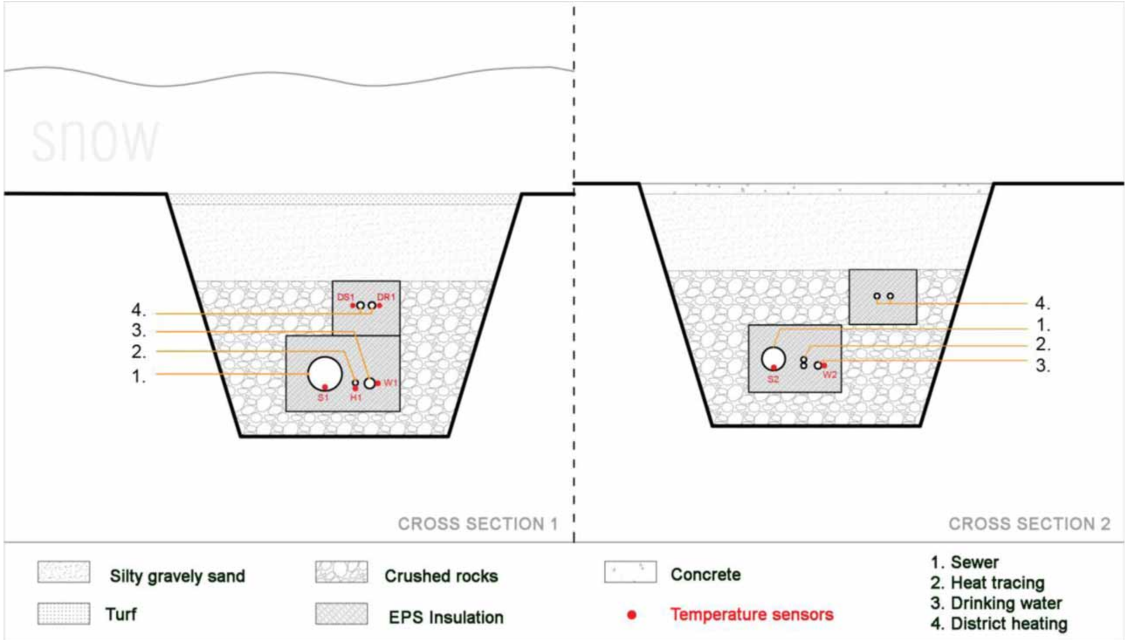

Figure 2 | Geometries of the studied cross sections and temperature sensors' locations. The full colour version of this figure is available in the online version of this paper, at http://dx.doi.org/10.2166/wst.2017.174.

The aim of the experiment was to determine, for each cross section, the influence of the heat tracing temperature T_H on the sewer pipe temperature T_S and the water pipe temperature T_W. To this end, the heat tracing water temperature was lowered by 5 °C every 12 hours from the district heating house station, and the temperature variations of T_H, T_S and T_W were recorded every 3 minutes using sensors installed in the utilidor (red markers on Figure 2). According to the manufacturer, the uncertainty of the temperature sensors is smaller than 0.5 °C in the temperature range −10 °C to 85 °C. The experiment was conducted when the tenants of habitations A1 and A2 were not at home in order to avoid water consumptions during the measurements. The reason for this was to investigate the consumption scenario where the pipes were most prone to freezing and overheating.

Modelling method

2D finite volume models of cross sections 1 and 2 (Figure 2) were built using the modelling software ANSYS CFX. The model size was 25% wider and 14% deeper than the trench size to avoid perturbations due to edge effects in the area of interest (the utilidor and adjacent soil). To account for the non-linear phenomenon of soil freezing, the soil thermal parameters were defined as temperature dependent. An undisturbed turf sample was taken at cross section 1, its dry density and water content were determined using a drying oven. The soil particle density of the same sample was determined with a pycnometer to estimate the turf porosity at the sampling location. Based on these values, the frozen and unfrozen thermal conductivity of turf were calculated according to the method proposed by Andersland & Ladanyi (1994) for organic soil. The frozen and unfrozen heat capacities of turf were also determined according to Andersland & Ladanyi (1994).

A similar procedure was used for the layer of silty gravely sand (Figure 2), but the frozen and unfrozen thermal conductivities were calculated according to Johansen's method (Johansen 1975) for mineral soils. The layer of crushed rocks could not be sampled, but an average grain size of 2 cm was estimated from pictures of the construction. Dry density and porosity values measured by StormTech (2012) on soil samples having a similar grain size (3/4 inches) were used to determine the thermal parameters of the crushed rock layer. The same calculation method as for the silty gravely sand was used, considering a water content of 6%. The thermal parameters used in the model are summarized in Table 1. The transition from unfrozen to frozen thermal parameters was modelled using the unfrozen water content curves suggested by Geo-slope (2008). The latent heat of water solidification was considered in the, temperature dependent, heat capacity function of the different types of soil.

Table 1 | Physical parameters of the materials used in the finite volume model. Values in parentheses correspond to frozen state

	Dry density *kg/m³*	Water content *m³/m³*	Porosity *m³/m³*	Thermal conductivity *W/m.K*	Volumetric heat capacity *kJ/m³.K*
Turf	300	0.32	0.5	0.18 (0.25)	3,320 (2,680)
Silty gravely sand	1,600	0.09	0.4	1.05 (0.82)	1,720 (1,540)
Crushed rocks	1,600	0.06	0.4	0.92 (0.69)	1,590 (1,470)
Concrete	2,400	–	–	0.8	1,800
EPS	28	–	–	0.035	32

A transient heat conduction analysis of the experiment presented on the previous page was conducted with the 2D finite volume models of the cross sections. The left and right boundaries conditions of the models were set as adiabatic. For the bottom boundary condition, an average geothermal heat flux of 0.08 W/m^2 was considered. The ground surface temperatures were set equal to the air temperature measured at the study site. Based on the Swedish Meteorological and Hydrological Institute data, a time-variable heat transfer coefficient was introduced at the ground surface of cross section 1 to model the insulation provided by the snow cover. A value of 0.25 W/m.K was assumed for the thermal conductivity of snow. The district heating and heat tracing pipes temperatures were set according to the measured values from sensors DS1, DR1 and H1. A pre-simulation of the year preceding the experiment was run to obtain the initial temperature field in the cross sections. A time step of one day was used for the pre-simulation. The experiment was then simulated with a time step of 60 minutes. The temperature evolutions at sensor locations S1, W1, S2 and W2 were plotted to study their response to the heat tracing temperature variations (values from sensor H1).

RESULTS AND DISCUSSION

The evolution of heat tracing temperature applied at cross section 1 during the experiment is seen in Figure 3. The temperature step of 25 °C was maintained during 36 hours because of water consumptions observed during the first 24 hours at this temperature. The other temperature steps (15, 20, 30 and 35 °C) were applied every 12 hours. Because of their proximity (3 metres), only a very small temperature drop was expected between cross sections 1 and 2. The heat tracing temperatures measured at cross section 1 (Figure 3) were therefore used for both cross sections when analysing the results. The measured and modelled pipes temperatures corresponding to each heat tracing steps of Figure 3 are presented in Figure 4

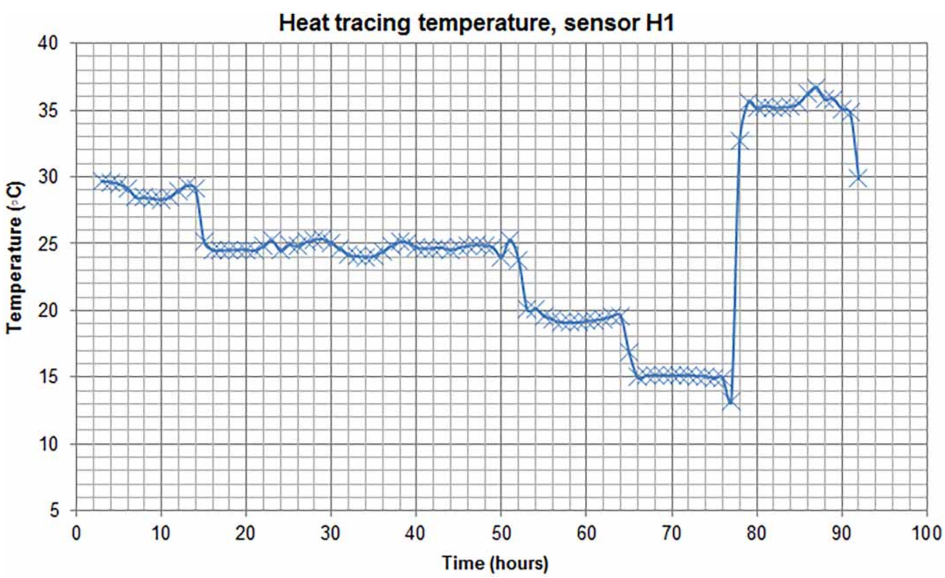

Figure 3 | Heat tracing pipe temperature applied at cross section 1 during the experiment.

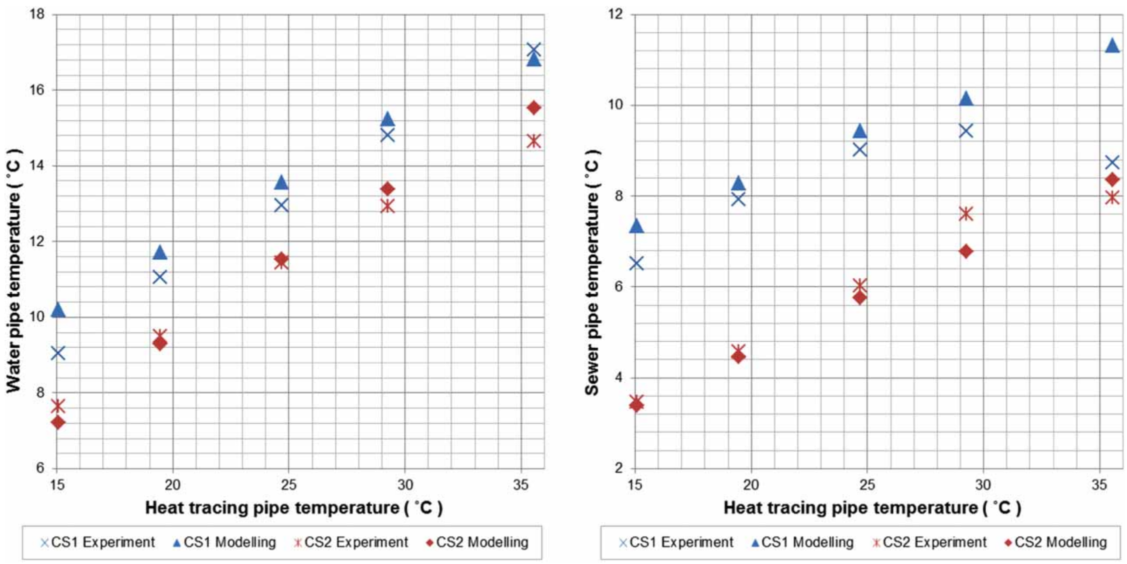

Figure 4 | Comparison of experimental and modelling results. Influence of heat tracing temperature on water (left) and sewer temperature (right) at cross sections 1 and 2.

for cross sections 1 and 2. The x-values of the data points correspond to the average heat tracing temperature applied during the heat tracing steps of 12 hours. The values on the y-axis correspond to the average water (Figure 4 left) and sewer (Figure 4 right) temperature during the last hour of each heating step.

The measured water pipe temperatures showed a linear dependence to the heat tracing temperature within the range [15; 35 °C] for both cross sections (data series 'CS1 experiment' and 'CS2 experiment', Figure 4 left). A linear regression model was fitted to these data series with the least square approach. Coefficients of determination of 0.99 were obtained for both cross sections, confirming the linear dependence of drinking water temperature on heat tracing temperature. The experimental results for the drinking water pipes also indicated that a heat tracing temperature of 15 °C was sufficient to prevent drinking water from freezing at both cross sections (temperatures of 9 and 7.6 °C for cross sections 1 and 2), under the studied climatic conditions. A heat tracing temperature of 15 °C could be achieved at these locations by having a low heat tracing flow and therefore an important temperature drop between the district heating house station and property A1 (drop from 30–35 °C to 15 °C). The results of the experiment also showed that heat tracing temperatures greater than 30 °C were leading to drinking water temperatures above 15 °C at cross section 1, which is favourable for bacteria growth (Ainsworth 2004). These results indicate that to preserve water quality, the system installed in Kiruna should be operated carefully to avoid heat tracing temperatures above 30 °C in snow-covered sections.

The measured sewer temperatures increased linearly for heat tracing temperatures below 25 °C. A linear regression model was fitted with the least square approach to the measured sewer pipe temperatures for heat tracing temperatures below 25 °C (data series 'CS1 experiment' and 'CS2 experiment' in Figure 4 right). The coefficient of determination was 0.98 for cross section 1 and 0.99 for cross section 2. For higher heat tracing temperatures, sewer temperatures at both cross sections showed a reduction of their rate of change. A suggested explanation for this is that high pipe temperatures enhanced the air flow in the sewer coming from outdoor (air at less than 0 °C) intakes. As presented in Figure 4, the sewer temperature at cross section 2 was measured to be 3.5 °C for the coldest heat tracing step. This is a relatively low temperature to prevent freezing risk, knowing that the system was not studied under a severe cold event and that cross section 2 was free of snow. However, heat tracing temperatures of about 25 °C provided a more reliable freeze protection to the sewage (6 °C measured at cross section 2), while keeping water pipes below 15 °C.

The difference in thermal behaviour between the snow-free and snow-covered section was significant. For each heat tracing level, the sewer and water pipe temperatures at cross section 2 were lower than at cross section 1. This difference was on average 1.8 °C for the water pipe and 2.4 °C for the sewer pipe. Larger gaps can be expected under colder climatic conditions though, which should be investigated in a future study.

The finite volume modelling results for drinking water temperature showed good fitting to measured data (Figure 4, left). Indeed, the coefficient of determination of the finite volume model for water pipe temperature was 0.93 for cross section 1 and 0.95 for cross section 2. The temperature dependences obtained by finite volume simulation also appeared to be linear, with slightly different slopes than the experimental results. The thermal finite volume model correlated well to the sewer temperature evolution measured for heat tracing temperatures lower than 25 °C, but did not explain the non-linear behaviour observed at higher temperatures during the experiment. The sewer temperatures were therefore overestimated for the 35 °C heating step (Figure 4, right). Within the heat tracing temperature range (15 °C; 35 °C), the coefficient of determination of the finite volume model for sewer pipe temperature had a value of −0.53 (very poor fit) for cross section 1 and 0.93 for cross section 2. However, a better fit was observed at cross section 1 within the heat tracing temperature range (15 °C; 30 °C) with a coefficient of determination of 0.70.

Deviations between predicted and measured values were smaller than 1.2 °C at both cross sections, with the exception of the sewer pipe at cross section 1 when heat traced at 35 °C (deviation of 2.6 °C from this measurement). These reasonable deviations and the moderate-to-high coefficient of determination values suggest that the finite volume model adequately simulated the phenomenon of frost penetration in the soil surrounding the utilidor.

CONCLUSION

In this paper, the thermal behaviour of two cross sections of a shallow utility corridor, freeze-protected with 4th generation district heating, was investigated experimentally and numerically. The main conclusion was that, under the climatic conditions of the study, a temperature of 25 °C for the heat tracing water is appropriate to prevent freezing of sewer and drinking water lines while keeping drinking water in a safe temperature range (between 10 and 15 °C). Also, the snow-free and snow-covered sections were affected differently by the heat tracing, with an average difference of 2.4 °C for the sewer pipe and 1.8 °C for the water pipe. Finally, the finite volume model showed good capability to predict the temperatures measured at both cross sections, with an exception for the gravity sewer pipe when heat traced, with water warmer than 30 °C. To improve design and operation practices, a wider range of cross sections should be investigated under typical and critical yearly temperature variations. The numerical model developed in this work was shown to be a functional tool to work in this direction. The sensibility of the model should be analysed beforehand though.

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REFERENCES

Ainsworth, R. G. (ed.) 2004 *Safe Piped Water*. IWA Publishing, London.

Andersland, O. B. & Ladanyi, B. 1994 *An Introduction to Frozen Ground Engineering*. Chapman & Hall, New York.

Bai, L. & Wang, Y. 2013 Numerical calculation of insulating layer thickness of rural water supply pipe in permafrost regions. *Advanced Materials Research* **864–867**, 2022–2026.

Coutermarsh, B. & Carbee, D. 1998 *Frost-Shielding Methodology and Demonstration for Shallow Burial of Water and Sewer Utility Lines, Report 98-4*, Cold Region Research and Engineering Laboratory, Hanover, NH, USA.

Freitag, D. & McFadden, T. 1997 *Introduction to Cold Regions Engineering*. American Society of Civil Engineers Press, Reston, VA, USA.

Geo-slope International Ltd 2008 *Thermal Modeling with TEMP/W 2007*. Geo-slope International Ltd, Calgary, Canada.

Gunderson, P. 1978 *Frost Protection of Buried Water and Sewage Pipes, Draft translation Report 666*, Cold Region Research and Engineering Laboratory, Hanover, NH, USA.

Haviland, R. A. 1983 Design process for utility distribution at Eielson A.F.B Alaska. In: *Proceedings of the First Conference on Cold Regions Environmental Engineering*, University of Alaska, Fairbanks, AK, USA, pp. 12–25.

Hazen, B., Thomas, J. E. & Thornburgs, D. B. 1990 Design and performance of the direct-bury water and sewer utilities in Barrow, Alaska, USA. In: *Proceedings of the Fifth Canadian Permafrost Conference, National Research Council Canada*, Laval, Quebec, Canada, pp. 397–402.

Johansen, O. 1975 *Thermal Conductivity of Soils, Draft Translation Report 637*, Cold Region Research and Engineering Laboratory, Hanover, NH, USA.

Kennedy, F. E., Phetteplace, G. E., Humiston, N. & Prabhakar, V. 1988 Thermal performance of a shallow utilidor. In: *Proceedings Volume 2 of the 5th International Conference on Permafrost*, Tapir Publishers, Trondheim, Norway, pp. 1262–1267.

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F. & Mathiesen, B. V. 2014 4th generation district heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy* **68**, 1–11.

Marques, R. C. & Monteiro, A. J. 2001 Application of performance indicators in water utilities management – a case-study in Portugal. *Water Science and Technology* **44** (2–3), 95–102.

McFadden, T. 1990 The Kilpisjarvi project: case study of cold-regions research in Finland. *Journal of Cold Regions Engineering* **4** (2), 69–84.

Pericault, Y., Hedström, A., Dahl, J., Vesterlund, M. & Olsson, G. 2016 District heat tracing of water and sewer lines in Kiruna, Sweden. In: *ARTEK Event 2016 - Sanitation in Cold Climate Regions*, Technical University of Denmark, Copenhagen, Denmark, pp. 88–89.

Raymond, D., Scothorn, P., Zhao, J. Q., Rajani, B. B. & Daigle, L. 1999 A practical measure to prevent frozen water service lines – the region of Ottawa Carleton's experience. In: *CSCE 1999 Annual Conference - 14th Canadian Hydrotechnical Conference*. Canadian Society for Civil Engineering, Montreal, Quebec, Canada, pp. 421–430.

Schubert, D., Crum, J., Jones, G. & Ronimus, A. 2013 Water distribution design and construction in Alaska-historic perspectives and current practice. In: *ISCORD 2013: Planning for Sustainable Cold Regions*, American Society of Civil Engineers Press, Reston, USA, pp. 840–851.

SMHI 2014a Normal medeltemperatur för januari (Normal average temperatures for January). Swedish Meteorological and Hydrological Institute, http://www.smhi.se/klimatdata/meteorologi/temperatur/normal-medeltemperatur-for-januari-1.3976 (accessed 26 January 2017).

SMHI 2014b Normalt största snödjup under vintern, medelvärde (Normal maximum snow depth during winter, average value). Swedish Meteorological and Hydrological Institute, http://www.smhi.se/klimatdata/meteorologi/sno/normalt-storsta-snodjup-under-vintern-medelvarde-1.7931 (accessed 26 January 2017).

Smith, D. W. 1996 *Cold Regions Utilities Monograph*. 3rd edn. American Society of Civil Engineers Press, Reston, VA, USA.

StormTech 2012 *Porosity of Structural Backfill, Technical Sheet #1*, StormTech, Wethersfield, USA. Available at: http://www.stormtech.com/download_files/pdf/techsheet1.pdf (accessed 24 January 2017).

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