Influence of air flow on temperature distribution in culverts, measurements versus prediction

Influence du débit d'air sur la distribution de la température dans les buses, mesures versus prédiction

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ABSTRACT: Uneven frost heave in roads and railways is a frequent problem in cold regions leading to degradation of structures. To improve drainage, culverts are frequently integrated into road and railway embankments. The presence of culverts changes the temperature distribution in the surrounding soil as cold air passes through the culvert. Consequently, frost depth and corresponding frost heave can be increased in the vicinity of the culvert compared to the rest of the structure. For an accurate frost related design, information of heat balance between the culvert and the surrounding soil is needed. A field study focusing on convective heat transfer in culverts was conducted in northern Sweden. Temperatures and air velocities in culverts of three sizes (0.6, 0.8 and 3.0 m) were recorded. Analysis of obtained data is presented with emphasis on the influence of air velocity on the temperature distribution within the culvert in relation to the size. Accuracy of trained gaussian process regression (GPR) models is estimated in predicting temperature distribution inside of a culvert based on ambient air temperature and air velocity inside the culvert.

RÉSUMÉ : Les déformations inégales du sol du au gel, sur les routes et les voies ferrées sont un problème fréquent dans les régions froides entraînant la dégradation des structures. Pour améliorer le drainage, des buses sont fréquemment intégrés dans les remblais routiers et ferroviaires. La présence de buses modifie la distribution des températures dans le sol adjacent, lorsque l'air froid circule dans les buses. Par conséquence, la profondeur du gel et le soulèvement qui en est la conséquence peuvent être augmentés à proximité de la buse, comparé au reste de la structure. Pour une conception précise prenant en compte les effets du gel, des informations sur l'équilibre thermique entre la buse et le sol adjacent sont nécessaires. Une étude de terrain portant sur le transfert de chaleur par convection dans les buses a été menée dans le nord de la Suède. Les températures et les vitesses de l'air dans des buses de trois diamètres (0,6, 0,8 et 3,0 m) ont été mesurées. L'analyse des données obtenues est présentée en mettant l'accent sur l'influence de la vitesse de l'air sur la distribution des températures dans la buse en fonction de son diamètre. La précision des modèles de régression du processus gaussien (GPR) entraînés est estimée en prédisant la distribution de la température à l'intérieur d'une buse en fonction de la température de l'air ambiant et de la vitesse de l'air à l'intérieur de la buse.

KEYWORDS: culvert, frost heave, cold climate, convective heat transfer

1 INTRODUCTION

Differential frost heave of roads is an enduring problem in the cold climate regions. Culverts are commonly included in road construction to allow water to flow from one side of the road to another. The introduction of culverts into the embankment can normally lead to increased frost depth around the culvert in seasonally frozen ground as cold air can enter the embankment structure through the pipe. Increased frost depth carries a greater potential for frost related damages if frost susceptible soil is present. Bumps and depressions over the culvert can often be seen on the road surface. For accurate frost related design of culverts, thermal boundary condition inside the culvert must be determined as it will allow for a more accurate prediction of frost depth around the culvert. It is apparent from that temperature distribution inside and around culverts is influenced but not limited to following factors: diameter, length, and material of the culvert, placement of the culvert in the embankment, outside temperature, air or water velocity inside the culvert, snow cover and solar radiation (Hua et al. 2014).

While culverts are designed to transport water, large fraction of them are dry during freezing periods due to low water levels. Therefore, it is reasonable to assume that there will be airflow through the culvert if the ends are unobstructed. Several previous studies note the occurrence of air flow in culverts, however influence of air flow and convective heat transfer on temperature distribution inside the culvert has not been extensively examined.

Zhang & Michalowski (2012) assumed that culverts are exposed to airflow in the winter and the temperature of the culvert is expected to be equal to the outside air temperature. Therefore, they used linearised temperature change of true air temperature data as the thermal boundary condition inside the culvert when modelling frost related damages around the culvert Hua et al. (2014) states that culvert serves as a large ventilation duct decreasing temperature difference between two sides of the embankment, caused by solar radiation. However, influence of air flow on culvert temperatures was not investigated further. Effect of convection between water flow and the wall of the culvert has been investigated by Périer et al. (2015) However due to the malfunction of instrumentation, effect of air temperature variation and flow was never investigated. Ventilation ducts that resemble culverts have previously been used to increase permafrost thickness. Design method for such ducts was proposed by Zarling (1984). An example calculation provided in the report suggest that pipe 1 foot (0.3 m) in diameter with air flow 1.5 feet/s (0.5 m/s) is a sufficient cooling system to freeze a talik of 3 feet (0.9) in diameter. Therefore, indicating the significance of air flow in a ground freezing process around a pipe. Influence of air flow on temperature distribution inside the culvert must be determined for future assessment of frost depth around culverts.

2 METHOD

Three culverts in Northern Sweden were instrumented using thermocouples and switching anemometers. Thermocouples were installed in three cross-sections inside the culverts, according to Figure 1. Temperatures were measured in half of the culvert as it was assumed that temperature distribution inside the culvert would be mirrored relative to the centre of the road. First cross-section (CS1) is located at the very entrance of the culvert, second cross-section appr. ¼ way inside the culvert and third cross-section appr. in the centre of the culvert. Sizes of instrumented culverts along with locations (distance from the entrance) of the cross-section are presented in Table 1.

Table 1. Location of thermocouples of instrumented cross-section in the culverts relative to the entrance

Culvert	*Total length*	*CS1*	*CS2*	*CS3*
3.4 m	30 m	4.0 m	6.3 m	10.2 m
0.8 m	17 m	0.05 m	4.6 m	8.6 m
0.6 m	10 m	0.05 m	4.1 m	6.6 m

Each cross-section consists of two thermocouples. In the 0.6 and 0.8 m culverts one is placed at the top and the other at the bottom of the culvert, according to Figure 1. As the 3.4 m culvert is used by pedestrians the bottom thermocouple is placed at the side of the culvert. One additional thermocouple is placed outside of each culvert above the expected snow level to monitor ambient air temperature. Switching anemometers are installed inside the culvert, 0.5 m from the entrance. Temperature and air velocity data are recorder hourly at all locations using CR1000x loggers produced by Campbell scientific. All three culverts can be considered dry during the freezing period.

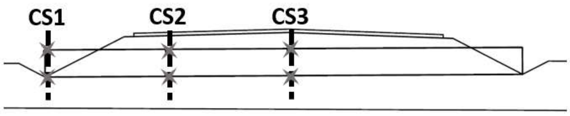

Figure 1. Location of thermocouples in 0.6 and 0.8 m culverts marked by stars

Based on the collected temperature data it is evident that air flow inside the culvert influences temperature distribution of the culvert. As air flow in the culvert increases, the temperature values inside the culvert become closer to the outside temperature. Whereas a low velocity airflow results in a larger difference between the temperature distribution in the culverts and ambient outside temperature. This effect becomes apparent from temperature and air velocity graphs at around 1m/s velocity, Figure 2. However, it is possible that air flow influences temperature distribution at lower velocities and the effect is not apparent based on visual analysis of the graphs.

To estimate the effect of air velocity on temperature distribution inside the three culverts, MATLAB Regression Learner (2020) was used to train serval models based on two factors, the recorded outside temperature and air velocity, to predict temperatures inside the culvert. A second set of regression models was also trained, based on outside temperature only as a factor, for comparison. If accuracy of the model increases with the addition of air velocity data to the regression model, air velocity can be considered as a significant parameter in determining temperature distribution inside the culvert. In each model, the temperature recorded by a thermocouple inside the culvert was used as a response variable while recorded air velocity inside the culvert and outside air temperature were used as predictors.

To estimate the accuracy and fit of the model root mean square error (RMSE) and coefficient of determination (R2) values are used. RMSE value shows the average deviation between predicted and true values while R2 shows proportion of the variation in predicted variable (culvert temperature) that can be explained by the independent variables (air velocity, outside temperature).

Two of the smaller culverts were closed by snow halfway through the freezing period. Therefore, only data for initial freezing period where air flow is present in the culverts is used for the regression analysis. For the 0.6 m culvert data for period of Oct. 10. 2020- Jan. 12. 2021 for 0.8 m culvert data for Oct. 10. 2020- Dec. 20. 2020, was included in the model. As the large the 3.4 m culvert does not become covered the whole recorded data set was used, Oct. 10. 2020- Jun. 6. 2021. During these time periods average/maximum air velocity inside 0.6 m, 0.8 m and 3.4 m are respectively 0.3/2.1 m/s, 0.1/0.8 m/s and 0.2/1.1 m/s. Average temperature difference between the centre of the culvert and recorded ambient air temperature is around 1.2 °C while max differences can reach 13°C for the 0.6 and 0.8 m culverts during the initial freezing period. While for the 3.4 m culvert, the average difference is 0.2 °C and maximum 12.0 °C, for the whole measurement period. Average temperature in all culverts was warmer than recorded outside air temperature.

3 RESULTS AND ANALYSIS

Regression analyses were carried out for each thermocouple location of the three culverts. Gaussian process regression (GPR) models, in MATLAB Regression Learner application (2020), provided the best predictions for all data sets. Four GPR models

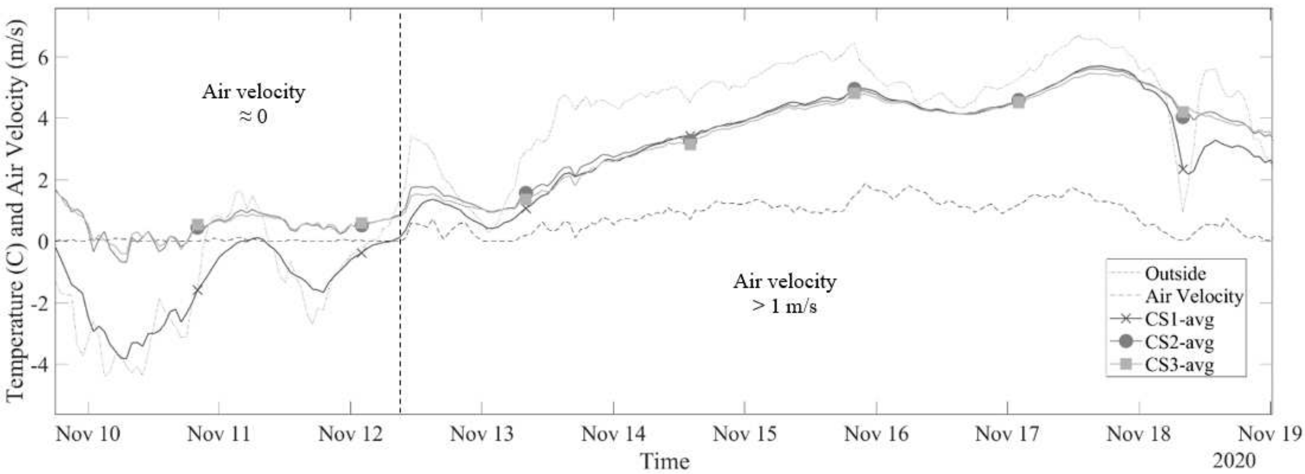

Figure 2. Influence of air velocity on average temperature distribution inside 0.6 m culvert

were used: rational quadratic, squared exponential, matern 5/2, exponential. Exponential and squared exponential GPR models provided usually a slightly better fit of predicted data indicated by smaller deviation from the standard mean- lower residual values. Largest differences between RMSE values of different Gaussian process regression models for all culverts were between 0.02 and 0.03 indicating minor variation between the models. Difference in R2 value between the models never exceeded 0.01. Therefore, any of the provided GPR models could be used for prediction with similar level of accuracy.

Accuracy of the regression models increases towards the entrance. The thermocouples at CS1 are installed in a section of the culvert that is not covered by soil. Temperatures at the location are very heavily influenced by the outside temperature, increasing the accuracy of the prediction. Using air velocity as a factor in GPR models at CS1 in addition to outside temperature provided less increase in accuracy compared to CS3. Therefore, temperatures at the entrance of the culvert seem to be not influenced by wind or air flow in a significant way. Further analysis will focus on thermocouples closer to the centre of the culverts as those temperatures are most difficult to predict and are the least influenced by the outside temperature.

GPR models using both air velocity and temperature provided a good fit for the 0.6 m and 3.4 m culverts. Accuracy of the models was lower for the 0.8 m culvert. Predicted temperature values for the bottom thermocouples in CS3 are used to compare the accuracy of the models between culverts. For all culverts removal of air velocity from the GPR decreased the accuracy of the model, indicated by increased RMSE value and decreased R2 value. RMSE and R2 values for all three culverts are given in Table 2.

Table 2. RMSE and R2 values of predicted temperature values at CS3 bottom thermocouples in the three culverts

Culvert	*Factors: air velocity and temperature*		*Factors: air temperature*	
	RMSE	*R^2*	*RMSE*	*R^2*
3.4 m	2.06	0.88	2.17	0.86
0.8 m	1.33	0.52	1.46	0.43
0.6 m	1.02	0.88	2.17	0.86

Least significant decrease in accuracy upon removal of the air velocity factor from the model occurs for the 3.4 m culvert. This culvert is more influenced by the outside temperature presumably due to its size. As temperature differences between the culvert and outside air are already smaller compared to the other two culverts, wind could potentially have less influence on temperature changes inside the culvert. RMSE values for temperatures of the 3.4 m culvert are larger compared to the two smaller culverts, as longer period of temperature measurements introduced a higher variation in values.

For the 0.6 m culvert GPR model accuracy improved upon addition of the air velocity factor, indicated by 3% increase in R^2 value. True and predicted temperature values inside the 0.6 m culvert can be seen in Figure 3.

Models based on the 0.8 m culvert provided the worst fit to the measured temperature data. However, increase in model accuracy of 0.8 m culvert was the largest of the three culverts upon addition of the air velocity factor to the model, R^2 value increased by 9%. Significantly lower accuracy of GPR model using data from the 0.8 m culvert compared to the other two culverts suggest that culvert might be subjected to different conditions and factors that have high impact on the temperature distribution of the 0.8 m culvert are unaccounted for in the model.

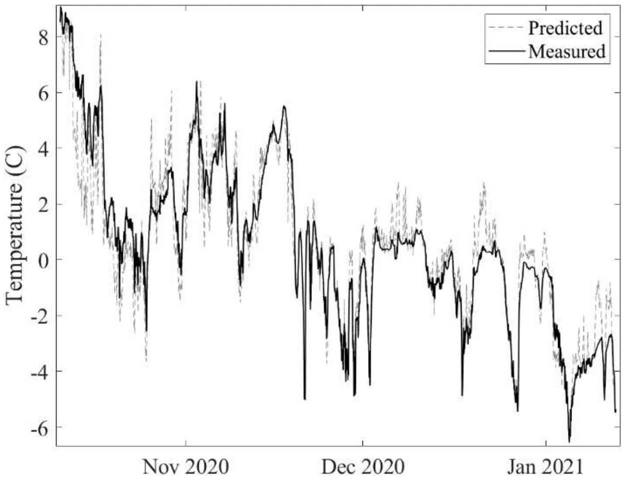

Figure 3. Measured and predicted temperatures using GPR model for the 0.6 m culvert CS3 bottom thermocouple

To compare the models for the 0.6 and 0.8 m culverts, predicted vs. actual response plots are used, according to Figure 4. For the 0.6 m culvert, data points are mostly concentrated around the perfect prediction line while data points for the 0.8 m culvert are more scattered indicating lower accuracy. Accuracy of both models decreases with increasing temperatures; however, the effect is significantly more prominent for the 0.8 m culvert.

To further investigate the effect of air velocity on temperature distribution, one low and high air velocity period was chosen for each culvert for regression analysis. Chosen time periods along with occurring velocities are presented in Table 3.

For the high velocity period, GPR model prediction remained more accurate if the air velocity was included in the model, based on the RMSE and R^2 values, especially for the 0.6 and 0.8 m culverts where R^2 value for the bottom thermocouple at CS3 increased by 12% and 16% respectively. For the 3.4 m culvert, the increase was only 2%, indicating further the decreased influence of air velocity on temperature distribution in larger culverts. R^2 values for the bottom thermocouples at CS3 were 0.78, 0.57 and 0.98 for the 0.6, 0.8 and 3.4 m culverts respectively, when air velocity was included in the GPR model.

The accuracy of the GPR models decreased for the 0.8 and 3.4 m culverts during the low velocity periods compared to the previously discussed high velocity periods. R^2 values for the bottom thermocouple at CS3 were 0.93, 0.36 and 0.43 for the 0.6, 0.8 and 3.4 m culverts respectively, when air velocity was included in the model. Upon inclusion of the air velocity factor, the accuracy of the GPR model was improved in all cross-sections for the 0.6 m culvert, improvement in R2 value 1% in CS3 bottom thermocouple and 3% in the top thermocouple. It should be noted that air velocity in the 0.6 m culvert is highest of the three culverts even during the low velocity periods. For the 0.8 m culvert, including air velocity in the model increased the R2 value in CS1 bottom thermocouple by 33% and decreased the R2 value by 36% in CS2 top thermocouple. For the 3.4 m culvert, the variation in R2 value was less drastic but it increases by 6% for top thermocouple in CS3 while decreasing by 5% for top thermocouple in CS2. Such variation in model accuracy for 0.8 and 3.4 m culverts suggest that when air velocity is low it should not be used as a factor in predicting temperature distribution inside the culvert. It is likely that a ratio of air velocity and size of the culvert has a governing effect on the temperature distribution. It should also be determined whether there is a certain culvert dimension from which the effect of air velocity can be disregarded entirely. For example, while it is apparent that the effect is negligible for this specific 3.4 m culvert it is not clear if this would be true for all culverts of similar size.

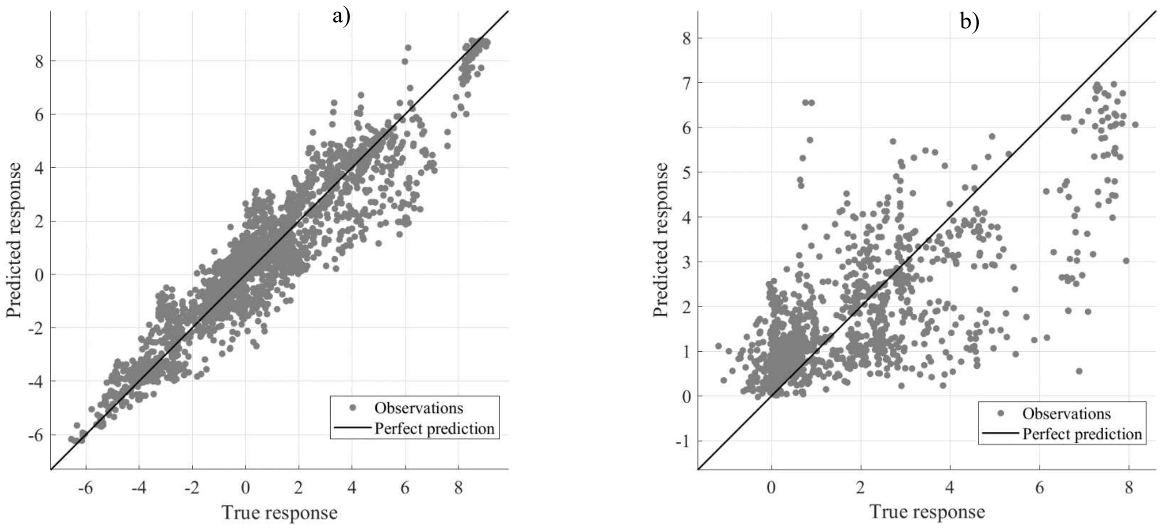

Figure 4. Predicted vs true response plots for bottom thermocouple at CS3 a) 0.6 m culvert b) 0.8 m culvert

Table 3. RMSE and R2 values of predicted temperature values at CS3 bottom thermocouples in the three culverts

		Culverts		
		3.4 m	*0.8 m*	*0.6 m*
High velocity period	Time	21.01.21-23.01.21	18.10.20-19.10.20	14.11.20-17.11.20
	Average velocity (m/s)	0.7	0.5	1.3
	Maximum velocity (m/s)	1.1	0.8	1.9
Low velocity period	Time	03.01.21-07.01.21	15.10.20-17.10.20	06.11.20-13.11.20
	Average velocity (m/s)	0.1	0.0	0.2
	Maximum velocity (m/s)	0.2	0.1	1.0

4 CONCLUSIONS

It is evident that air velocity can be a significant factor in determining thermal boundary inside culverts under certain high velocity conditions. The magnitude of air velocity that can be considered of significant impact has to be determined. Furthermore, it appears that several other factors must be contributing to the temperature distribution inside the culvert. While it is known that these additional factors are likely- size and placement of the culvert, water flow inside the culvert, solar radiation, and snow cover it is not clear how significant their influence is. Factors influencing temperature distribution of culverts in a significant manner must be accounted for when estimating the thermal boundary inside of the culvert. Increased knowledge of temperature distribution inside the culvert will allow for a more accurate frost related design of culverts, increasing road safety and decreasing resources spent on maintenance.

Gaussian process regression models trained based on both outside air temperature and measured air velocities inside the culvert are better at predicting measured temperatures inside the culvert compared to models trained just on measured outside temperatures. Increase in R2 value upon inclusion of air velocity is 2-9% depending on the culvert.

Prediction accuracy of the large 3.4 m culvert is least affected by inclusion of air velocity in the model. The effect of air velocity on the temperature distribution inside the culvert is insignificant for larger culverts. For the 0.8 m culvert inclusion of air velocity significantly increase the accuracy of the model (increase in R2 value by 9%) the model does not provide a very good fit for the temperature data compared to the other two culverts, R2 of 0.52. It is likely that more significant factors than air velocity are contributing to the temperature distribution.

When high air velocity periods were analysed, accuracy of the GPR models for the 0.6 and 0.8 m culverts increased with addition of air velocity data. The R2 values increased by 12% and 16% respectively, indicating significance of air flow at higher velocities. The effect of air velocity on temperature distribution seems to be significant at average velocities as low as 0.5 m/s as indicated by the results from the 0.8 m culvert.

5 ACKNOWLEDGEMENTS

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