Influence of water temperature and flow on thermal regime around culverts built on permafrost.

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ABSTRACT
Embankment instability is frequently observed on the Alaska Highway in Yukon (Canada). Some of the instability problems are close to culverts. Free air and water circulation through the culvert creates a thermal disturbance to the surrounding soil. Two culverts near Beaver Creek were instrumented to document such disturbances. Soil temperatures around the culverts were recorded for an entire year while water temperatures and flow were recorded during both spring and summer. These data allow validation of mathematical relations established between the heat flux below the culvert and water temperature and flow. Variations in flow and water temperature were simulated in the mathematical model to determine the influence of these two parameters on the heat flux transmitted from the culvert to the ground.

RÉSUMÉ
Sur l'Alaska Highway au Yukon (Canada), des problèmes d'instabilités sont fréquemment observés et certains sont aux abords de ponceaux. En autorisant la libre circulation de l'air et de l'eau à travers une conduite, des perturbations thermiques additionnelles sont infligées au sol environnant. Afin de documenter ces perturbations, deux ponceaux ont été choisis et instrumentés. Les températures du sol autour des ponceaux ont été enregistrées pendant une année entière tandis que la température de l'eau entrant et le débit ont été enregistrés pendant deux printemps et étés. La collecte de ces données a permit de valider une relation mathématique établie liant le flux de chaleur sous le ponceau avec la température de l'eau et le débit. Finalement certaines variations de débit et de température de l'eau ont étaient appliquées sur le modèle mathématique afin de quantifier ces deux paramètres sur le flux de chaleur transmis du ponceau au sol.

1 INTRODUCTION

In permafrost areas, construction of road embankments modifies the thermal regime of soil beneath and next to the road. Disturbance to the thermal conditions may result in thaw of permafrost and infrastructure degradation.

Water circulation in a culvert may increase the heat input and create further disruption to the thermal regime. Settlement may occur in ice-rich permafrost areas causing culvert damage, poor water management, and considerable permafrost degradation beneath the road. Several problems associated with culverts can be observed along the Alaska Highway, including culvert distortion, joints coming apart causing water to flow underneath the culvert, and culvert collapse.

2 BACKGROUND

Several studies on the impact of culvert construction have been completed in China. Zhang and Wang (2007*)* concluded that culvert construction during the freezing period has a minor impact on permafrost degradation. They observed that air circulation in the culvert generated more temperature variation near the sides of the embankment than in the center. In consequence, the permafrost table was higher beneath the middle of the culvert than at the ends of the structure. However, they observed that soil temperatures beneath the culvert were higher than at similar depths in the rest of the embankment.

Zhang (2014) developed a thermal-hydro-mechanical model to simulate thawing and freezing around culverts. He showed that during a short freezing period a bump appeared above the culvert but over a long period a dip occurred. Frost penetrated downward from the surface and upward from the culvert into the fill. Initially, frost penetration was greater above the culvert than to each side, causing a bump. Later when frost penetration in the embankment had passed the culvert and temperatures remained below 0°C, heave at the culvert ceased but not in the soil at depth, causing a dip above the culvert. To reduce these effects, complete insulation around the culvert's wall was analyzed. The insulation reduced frost penetration from the culvert up to the soil surface and reduced bumping but did not stop a dip forming.

Another study on thermal regime between culvert and soil was conducted by Liu et al. (2014). These authors considered 3 culvert shapes: rectangular, circular, and arched. They observed that a circular pipe has a lower impact on the thermal regime than a square design in winter, but the opposite in the thawing season. This effect is due to the geometry of the heat exchange surface. Additionally, the authors studied two insulation designs. The first was an application at the entire culvert's length and the second at the embankment's shoulder. They noticed a reduced temperature perturbation with insulation along the entire length. They concluded that the impact of the culvert on the thermal regime of the soil may be ignored if the insulation has good thermal properties and a substantial thickness.

The Transportation Association of Canada has published guidelines for culvert design in permafrost environments (TAC 2010). In ice-rich areas, TAC recommends building a 1.5 m thick granular protection layer underneath the culvert to limit permafrost disturbances. Also, to compensate for uncertainties due to permafrost conditions and to protect against soil compressibility, TAC (2010) recommends a culvert gradient of between 1 and 2% and incorporation of a camber in the middle of the culvert. The culvert should have a large opening and thick walls if installed above permafrost. In addition, culverts should be riveted to prevent stresses due to soil movement. In Yukon, a common practice consists of placing insulation underneath the culvert and on its sides to keep the soil frozen and protect the culvert from soil movement. The best practice is to place insulation just after the winter to keep the soil frozen. Insulation reduces heat transfer from the surface to the permafrost, but it also lowers heat extraction from the permafrost below the insulation.

3 OBJECTIVES

To our knowledge, no information on the impact of water circulation through culverts on permafrost degradation is available. Furthermore, there is no known method for culvert analysis based on heat exchange between culvert and soil. The objectives of this paper are 1) to improve knowledge on the impact of water circulation through culverts on permafrost degradation beneath the embankment; 2) to document the thermal regime around culverts built on permafrost; and 3) to quantify the effect of flow and water temperature on the thermal regime.

4 METHODOLOGY

A mathematical model linking the heat flux between the culvert and the embankment to water flow and water temperature was developed and calibrated using data from two instrumented culverts on the Alaska Highway near Beaver Creek, YK. The culverts were instrumented in spring 2013 and monitored during summer in 2013 and 2014. The model was then used for a factorial analysis of the effect of water flow and temperature on the thermal stability of permafrost using a numerical simulation.

5 INSTRUMENTATION

5.1 Soil temperature measurement

In spring 2013, two thermistor probes were installed around an existing culvert at the Beaver Creek test site (Figure 1) Each probe contains three thermistors that measure soil temperature at the surface of the culvert, at 15 cm and at 30 cm. The probes were installed at the bottom and on the side wall of the culvert. It was very difficult to drill in the culvert wall because the soil was frozen and culvert diameter restricted access. Another culvert was instrumented during construction at the Border Culvert site (Figure 2). This allowed installation of longer thermistor cables and instrumentation without drilling through the culvert, so there is no circulation of water through the hole.

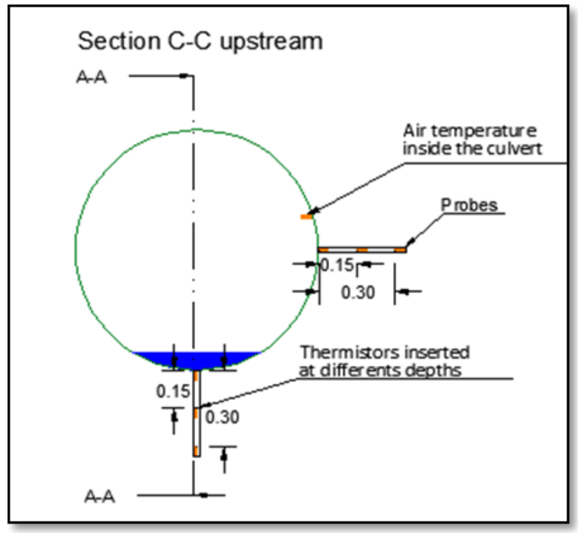

Figure 1 : Instrumentation at Beaver Creek site

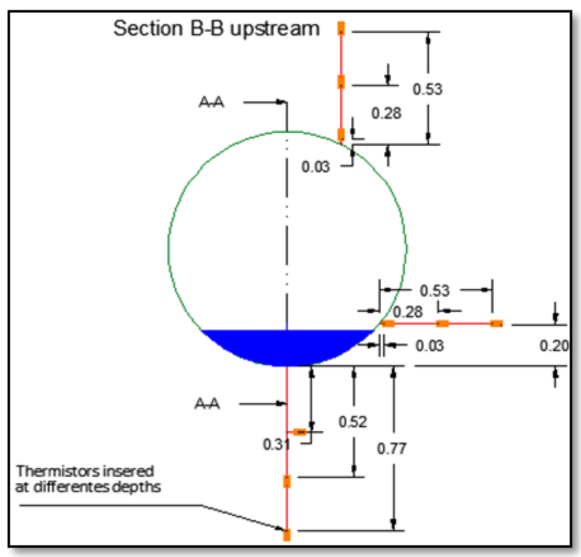

Figure 2 : Instrumentation at Border Culvert site

5.2 Water flow and temperature measurement

In spring 2013, a V notch weir and a pressure meter were installed upstream of the culvert inlet at the Beaver Creek site (Figure 3). Water height in the weir was calculated from the difference between the water pressure and the air pressure, and water flow was calculated from the height. Additionally, a thermistor was installed to measure the water temperature on the V notch weir.

Figure 3 : V notch weir at Beaver Creek site

Unfortunately, the water made its way under the weir that summer. Therefore, a different system was installed at both sites in spring 2014 to measure the water flow (Figure 4). The system allows assessment of water flow based on measurements of water level and water velocity.

Figure 4 : Flow measurement system in the second year. Water velocity was measured by the lower sensor, shown submerged, and water height by the upper sensor.

6 MATHEMATICAL MODEL

6.1 Heat transfer

The heat flux into the ground underneath a culvert depends on water flow rate and water temperature. According to the Fourier's Law (eq. 1), the heat flux is a function of a temperature difference and a thermal coefficient, U:

$$\delta = U\,(T_w - T_{pmf}) \qquad [1]$$

where δ is the heat flux expressed in W/m², T_w is the water temperature in °C and T_{pmf} is the temperature at the top of permafrost, considered equal to 0°C in this case.

The thermal coefficient, U (W/m².K), is defined by eq. 2 as the inverse of the thermal resistance, R:

$$U = \frac{1}{R_f + R_p + R_s + R_i} \qquad [2]$$

where R_f, R_c, R_s and R_i (m².K/W) are the thermal resistances of fluid, culvert wall, soil, and insulation respectively. In a case of a culvert, heat will be exchanged by convection between the water and the culvert's wall, by conduction through the culvert's wall and finally by conduction through each soil's layer encountered and the insulation.

The thermal resistance of convection R_{cv} given by eq. 3 is equal to the inverse of the convection coefficient of the fluid acting on the wall, h_c (W/m².K);

$$R_{cv} = \frac{1}{h_c} \qquad [3]$$

The thermal resistance for conduction R_{cd} is expressed by eq. 4 and is equal to the thickness of the component encountered, e_n (m), divided by its thermal conductivity k_n (W/m.K).

$$R_{cd} = \frac{e_n}{k_n} \qquad [4]$$

The unknown parameter is the convection coefficient h_c. It can be determined as a function of the water flow, as it depends on the culvert's dimensions and on water properties, i.e., specific heat capacity, dynamic and kinematic viscosities, thermal conductivity, and water velocity.

The coefficient h_c can deducted from the Nusselt number given by eq. 5:

$$N_u = \frac{h_c \times \emptyset_h}{k} \qquad [5]$$

where k is the water thermal conductivity (W/m.K), and the hydraulic diameter $\emptyset_h$ (m) may be calculated with eq. 6:

$$\emptyset_h = \frac{4S_m}{P_m} \qquad [6]$$

S_m and P_m are respectively the wet area (m²) and the wet perimeter (m).

To determine the Nusselt number, we must know whether the flow is laminar or turbulent. This can be determined using the Reynold's number with eq. 7:

$$R_e = \frac{V \times \emptyset_h}{v} \qquad [7]$$

where v is the water velocity (m/s), and v is the kinematic viscosity (m²/s). The *Reynolds number* is dimensionless. If it is higher than 2000, the flow is turbulent, if it is lower than 2000, the flow is laminar.

The second step is to characterize the velocity distribution with the Prandtl number, given by eq. 8:

$$P_r = \frac{\mu \times C_p}{k} \qquad [8]$$

where μ is the dynamic viscosity (kg/m.s), C_p is the specific heat capacity (J/kg.K) and k is the thermal conductivity. The Prandtl number is dimensionless. The higher the Prandtl number, the more influence the velocity will have on heat transfer. As this number depends on the properties of water, it can be considered a constant for our purposes.

For the properties presented in the Table 1 and water velocity and hydraulic diameter recorded in the field, the Reynold's number is higher than 2000 and the Prandtl number is 11.5.

Table 1: Thermal properties of water

Properties	
Heat capacity (J/kg.K)	4180
Thermal conductivity (W/m.K)	0.56
Kinematic viscosity (m²/s)	$1.6x10^{-6}$
Dynamic viscosity (kg/m.s)	$1.\ 6x10^{-3}$

Therefore, it is a case of forced convection in a turbulent pipe flow. For these conditions, the Dittus-Boelter equation may be used to determine the Nusselt number*:*

$$N_u = 0.023 \times P_r^{1/3} \times R_e^{4/5} \quad [9]$$

Knowing the Nusselt number, the convection coefficient h_c can be deduced from eq. 5.

Also, the velocity can be expressed by eq. 10:

$$V = \frac{Q}{S_m} \quad [10]$$

where Q is the water flow (m^3/s).

It is thus possible to deduce h_c as function of the flow inserting eq. 10 and eq. 6 in eq. 7, eq. 7 and eq. 8 in eq.9, and finally eq. 9 and eq. 6 in eq. 5 to obtain eq. 11:

$$h_c = \frac{Cst \times Q^{4/5} \times P_m^{1/5}}{S_m} \quad [11]$$

where Cst is a constant that is a function of the water properties.

6.2 Validation of the model

The following eq. 12 represents the mathematical model linking heat flux to water temperature and water flow. In the case of a pipe, the cylindrical coordinate should be used.

$$\delta = \frac{\theta.(T_w - T_{pmf})}{\frac{r_{ci}.S_m}{Cst.Q^{4/5}.P_m^{1/5}} + \frac{\ln(r_{ie}/r_{ii})}{k_i} + \sum\frac{\ln(r_{se}/r_{si})}{k_s}} [12]$$

θ is the angle where the flux is applied, r_{ci} is the inside culvert radius, r_{se} and r_{si} are the outside and inside soil radius, k_i and k_s are the insulation and soil thermal conductivities. The inside and outside wall temperatures may be considered the same because the wall thickness is small.

The model was validated using temperatures measured on the field. Figure 5 and Figure 6 show the flux calculated with the model against the flux measured under the culvert with thermistors placed at different depths. The model was validated for both study sites, i.e. Beaver Creek and the Border culvert.

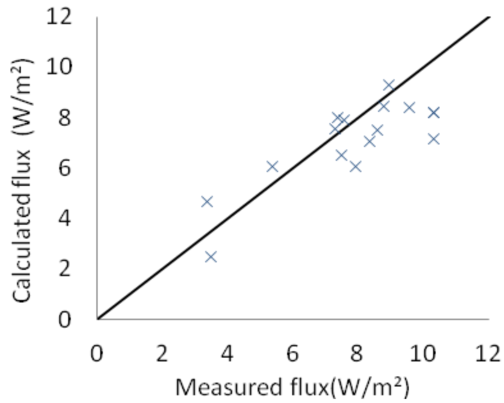

Figure 5 : Model validation at Beaver Creek site.

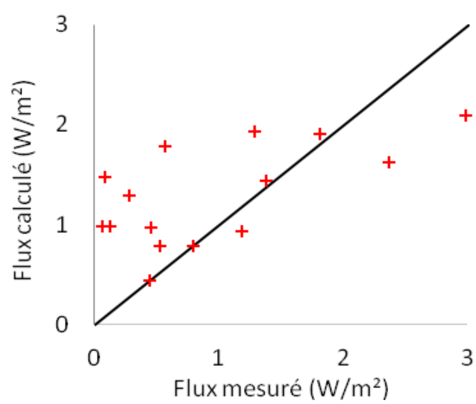

Figure 6 : Model validation at Border Culvert site

The correlation is generally good with r^2 = 0.67 at the Beaver Creek site and r^2 = 0.44 at the Border Culvert site. The residuals to the 1:1 lines are due to sensitivities to water temperature and the thermal properties of soils between the surface and the permafrost, which were approximated.

At the Beaver Creek test site, water temperatures were measured in the basin behind the weir, some distance from where the flux was measured. Moreover, the culvert wall was drilled to insert the probe. Attempts were made to seal the holes after installation but the sealants were applied in wet conditions. Seepage at this location may have affected the temperatures measured.

At the Border culvert site the water temperature and water flow were measured in better conditions so the model predictions should more accurate. Furthermore, the thermistors were placed deeper in the fill and no infiltration is likely to occur at that location because the culvert wasn't drilled to insert the probes. The measured heat flux is thus more reliable at that site. However soil properties were more uncertain than at the Beaver Creek site and contributed to the poorer correlation.

7 RESULTS

Results from the simulations are presented in Figure 7. Red lines represent flow variation and blue lines water temperature variation. Initial heat flux calculated with field conditions is represented by the black line. Sensitivity analyses simulated the following cases:

1) An almost dry pipe with 0.01 and 0.05 times the field flow;
2) A half empty pipe with 12 times the field flow;
3) A full pipe with 23 times the field flow.

Simulations of water temperature did not exceed 25°C or drop below 10°C. Finally, temperature was simulated with variations of 0.5 and 1.5 times the daily field water temperature (°C) and the field flow.

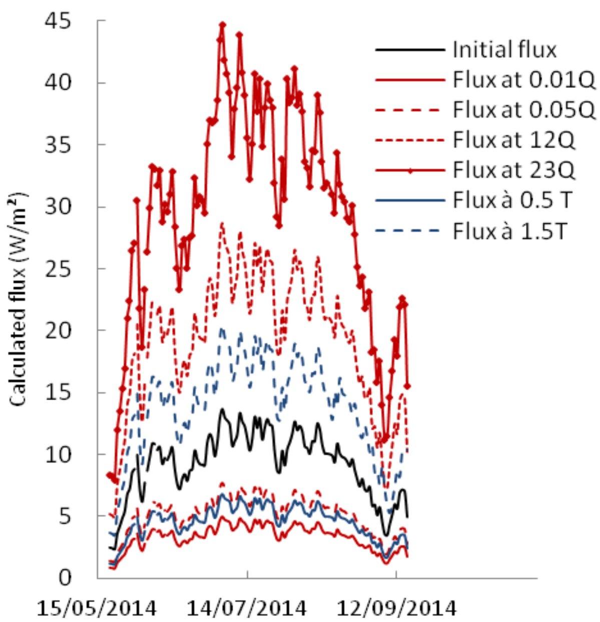

Figure 7 : Variations in heat flux during sensitivity analyses for water temperature and flow.

The reduction of water flow to 0.05Q resulted in approximately the same heat flux variation as caused by a reduction of water temperature to 0.5T. Similarly the increase of water temperature to 1.5T (factor 1.5) led to the same heat flux variation as caused by an increase in water flow to 5Q. This suggests that the heat flux underneath a culvert is much more sensitive to water temperature than to water flow.

8 DISCUSSION

This study is intended to support the development of a design procedure for low impact drainage systems in permafrost environments. It should support selection of an allowable water flow in a given context to avoid significant thermal disturbance to permafrost beneath the structure. The model presented may be used to estimate heat flux induced underneath a culvert based on water temperature and flow rate. This information will be used in a 2D thermal model to assess thaw depth as a function of heat flux. In the next steps of the project, the modeling results may allow the development of a practical tool to determine the allowable water flow in a culvert. Based on that information, it will be possible to select the number of crossings required to drain a watershed effectively across a road in sensitive permafrost conditions.

Results show that heat flux calculations are very sensitive to water temperature. This is a function of the climate and the geomorphologic and topographic characteristics of the site. A reliable relationship between surficial water temperature and site characteristics will need to be developed in order to support the application of the design method.

At Beaver Creek, instrumentation of the culvert was very difficult and several problems were encountered. Some data were altered during recording. A short circuit in the logger stopped the monitoring of air temperature and soil temperature on the side of the culvert. Consequently just one week of data was available the first year. For these reasons, the influence of air temperature in the culvert was not taken into account in the model. Therefore, additional analysis is required to finalize the heat balance analysis considering the effect of air temperature inside the culvert, mainly during winter.

At Beaver Creek, the instrumented culvert was removed and replaced after two years of monitoring due to its poor condition. Water seepage underneath the culvert certainly affected the temperatures recorded at that level. The impact of this problem is believed to minor but the model developed may be biased as a result.

Finally, in the mathematical model, heat flux was calculated using temperature measurements at the culvert entrance. It is likely that maximum heat exchange occurred at that location. However, it would be interesting to extend the study to the whole culvert length to evaluate the total heat transfer in the pipe and support the development of a 3D model.

9 CONCLUSIONS

Two culverts were instrumented on the Alaska Highway in Yukon. Soil temperatures were recorded for a year adjacent to the culverts, while water temperature and flow were measured in spring and summer.

The convection coefficient for the heat transfer between water and the wall of the culvert was established using the Reynolds and Prandlt numbers in the Dittus-Boelter equation. The approach takes into account the flow. Finally, a mathematical model was developed linking heat flux with water temperature and flow using the convection coefficient and Fourier's Law.

The model was validated with data from both of the two sites. The model gave a reliable prediction of heat flux, particularly for the Beaver Creek site with a determination coefficient equal to 0.67. Some slight differences are visible between the measured and calculated fluxes, which may be due to the measurements of water temperature being taken relatively far from the location of heat flux measurements. At Border Culvert site, we expected better results but the determination coefficient is equal to 0.44. Soil thermal properties were approximated and uncertain, which may explain the poorer correlation of this site.

Simulations of heat flux were made to quantify the effect of flow and water temperature on heat transfer to the soil beneath the culvert. The heat flux is insensitive to water flow, but varies greatly with temperature.

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