Evaluating the use of Distributed Temperature Sensing for permafrost monitoring in Salluit, Nunavik

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Fiber optics distributed temperature sensing (DTS) is a new technology. It opens the doors on original approaches to study permafrost temperature regime in a variety of environmental settings and engineering situations. An opportunity presented itself to try this new technology in 2012 as it was decided to rebuild the Salluit road to the community airport. It had been seriously impacted by permafrost degradation. A total length of 3.4 km of DTS cable was buried under the embankment slope, on both sides of the road. The data obtained allowed detection of localised heat sources along its length and gave temperature variations both in time and space since 2012.

RÉSUMÉ
La mesure de température linéairement distribuées à l'aide de fibre optique (DTS) est une nouvelle technologie qui ouvre la porte à des approches originales pour étudier le régime de température du pergélisol dans une variété de contextes environnementaux et des situations d'ingénierie. C'est en 2012, lorsque le ministère des Transports du Québec (MTQ) a décidé de reconstruire la route reliant l'aéroport de Salluit au village gravement affectée par la dégradation du pergélisol que l'idée d'essayer cette nouvelle technologie a été initialement retenue. Un total de 3.4 km de câble DTS a été placé sous le remblai de part et d'autre de la route. Les données de température linéairement mesurée à l'aide du DTS a permis la détection de sources ponctuelles de chaleur tout au long de la route et a aussi permis d'observer la variation spatiale et temporelle de la température depuis 2012.

1 INTRODUCTION

The impact of global warming on permafrost degradation is now tangible. The stability of urban and transport infrastructures in northern regions is now seen as a daily challenge (Allard et al., 2012). In Salluit, the permafrost beneath the road to the airport consists of very ice-rich post-glacial marine silt. It puts the road at high risk of deterioration by permafrost thawing**,** following any input of heat that may occur anywhere along its length (Allard and L'Hérault, 2010), the most feared heat sources being snow insulation on the shoulders in winter and water seepage underneath the structure in summer (Allard et al., 2007).

About 900 m long of the embankment was rebuilt and specially designed heat drains were buried under one side of the road to cool the embankment under snow in winter. On the other side of the road, the geometry of ditches and culvert was redesigned to reduce heat advection by water infiltration in summer. In addition to thermistors strings at selected control and sampling sites, a total length of 3.4 km of DTS cable were buried under the embankments slopes on both sides of the road**.**

The installation of DTS cable allows detection of localised heat sources anywhere along its length and to accurately measure temperatures variation both in time and space under the embankment of the Salluit road (Figure.1). The installation of the DTS system was a great opportunity to improve the knowledge of permafrost dynamic along the transportation infrastructure and select correction solutions.

2 DISTRIBUTED TEMPERATURE SENSING (DTS)

The DTS technology has been used over the past several years for a wide range of applications (Ukil et al., 2012) as power cable monitoring (Yilmaz and Karlik, 2006), pipeline monitoring (Nikles et al., 2004), well and reservoir monitoring (Kersey, 2000), fire detection and many more. The DTS technology is also used for numerous environmental studies such as a monitoring system for ecological characterization (Selker, 2008) or streamflow dynamics (Selker et al., 2006). However this technology had never been used for monitoring permafrost temperature along a linear infrastructure, making this study a premiere.

The DTS operation consists of a light pulse launched by a laser and travelling along the optical fiber to be partially reflected at the source when the signal passes from one environment to another. However the frequency of the reflected light is slightly different from the one emitted. This frequency shift corresponds to an energy exchange between the light beam and the ambient environment (Soto et al., 2007). As we know the light propagation speed in an optical fiber, the distance can be determined by the round trip time of the signal. The exact position of the temperature reading is determined by measuring the arrival time of the pulse signal on its return.

2.1 DTS cable and system specifications

The DTS cable used here is produced by AP Sensing GmbH and is characterised by two optical fibers which are embedded in a stainless steel shield and wrapped by an outer sheath. This cable has a high tensile and compressive strength. The cable is waterproof and is well protected against rodents. This cable is also provided with an outer sheath of flame-retardant halogen-free materials. This fiber is multimode type and it has the ability to transport multiple light frequency signals.

It`s core is made from a 50 microns diameter quartz heart, with a 125 micron sheath for a final coating diameter of 245 microns with its metal sheath and rubber finish. The total diameter of the cable is 3.8 mm and the weight is 25kg / km. The minimum curvature radius is between 15 x 20 x D mm and its crushing strength is 960 N / cm. The cable must be within a temperature range of 40°C to 85°C but it is strong enough to withstand temperatures between -50°C and 150°C. The linear resolution of the system is 0.25 m and the temperature measurement precision is 0.1°C. The data logging system was programed to take readings every 2 hours over a year.

2.2 The DTS installation steps

The fiber optics installation started in June 2012 and has been completed five months later as it progressed at the pace of repair works along the road. A total length of 3.4 km of DTS cable were buried under the embankments slopes, on both sides of the road. At the same time a heat drain was installed on the left-hand side of the road (Lamontagne et al., this volume). On the right-hand side of the road (towards the airport) the cable is buried at two depths (0.3 and 0.8 m) to detect heat carrying water seepage in the ground. On the left-hand side of the road, another fiber optics cable is buried under the heat drain to assess its efficiency in cooling back the permafrost under the road.

In addition a section of the cable measures ground temperature 0.25 cm deep in the natural terrain at several metres off the roadside as a reference. The cable also runs in loops across the road under four culverts. The GPS position was taken every meter along the cable using a Trimble VX Spatial Station and was linked to the reference number on the cable. On both sides of the road, a small section of the DTS cable (50 m) was placed next to a thermistors cable of 25 sensors to calibrate and make sure the accuracy of the DTS values (Figure.2).

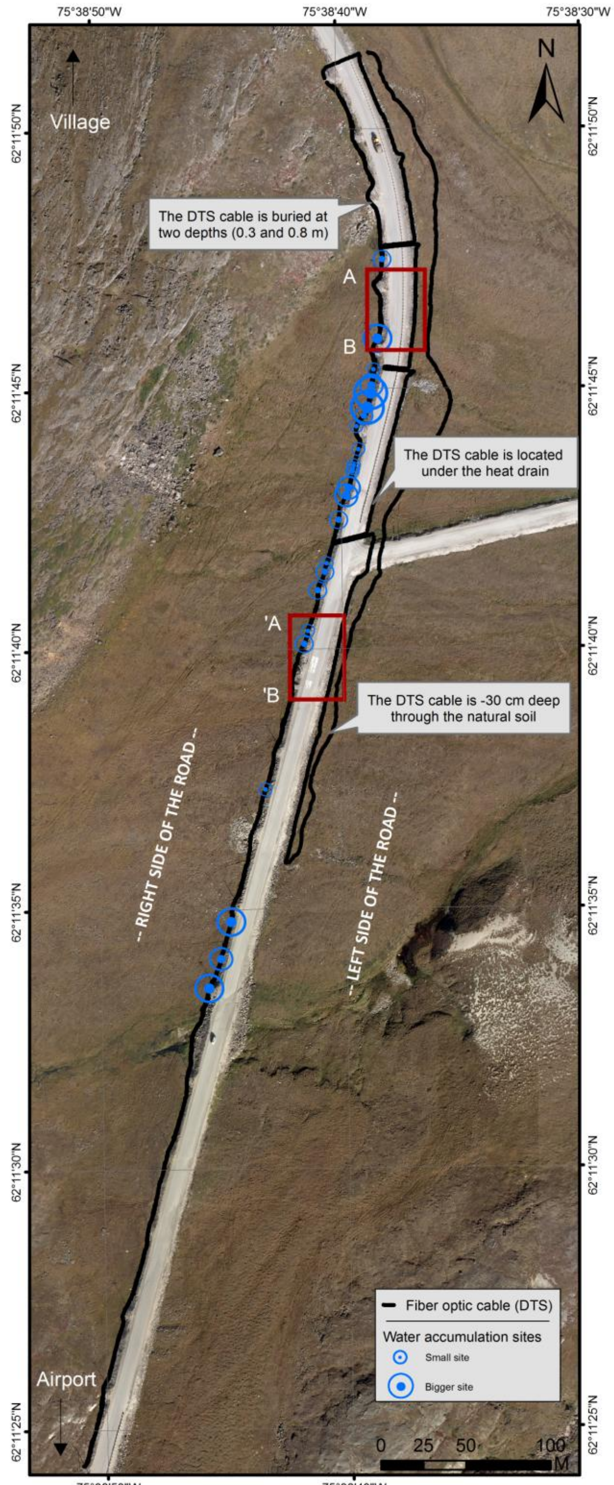

Figure 1 The DTS cable and water accumulation location along the road. The circles size are proportional to the water accumulation size.

2.3 Data acquisition

Data acquisition started on 12 October 2012. The DTS acquisition system (DTS logger) is set to take data every 2 hours at every 0.25 m. In total 163 200 data are recorded every day. That is 59 568 000 data every year. However only data at every metre are used to be matched with the GPS coordinates which are taken every metre.

2.4 Data management

Once downloaded the data files extension is modified to be incorporated in a SQL database designed and hosted by the Centre d'études nordiques (CEN). The integration of the data into the database allows structuring the informations and can be used to produce several types of data statistics. Once integrated and structured into the database, the data are matched with their respective coordinates from a SQL function. This crucial step is essential to allow the spatial analysis of temperature variations both in time and space.

3 RESULTS

Two full years of data have been collected since the implantation (2013-2014) of the distributed temperature sensing system for a total of more than 100 million data recordings. To assess the accuracy of the DTS sections along both side of the road were correlated with thermistor strings composed of 25 individual thermistors, used over the past several by CEN. The DTS data section which was compared with the thermistor strings exposed a strong correlation coefficient (R^2) between each other (Figure.2). On the right-hand side of the road, the correlation coefficient (R^2) between DTS data and thermistor data was of 0.86 on September 1, 2014. On the left-hand side of the road, the same coupling has a correlation coefficient (R^2) of 0.79 for the same date. The minor differences between the DTS data and thermistor data can be attributed to the geolocation of the cables and slight differences in depth which may vary from each other.

The cable appears to be highly resistant to freeze-thaw cycle which may exert significant tension on the cable. Only two breakings of the cable occurred along its whole length. The first one is located on the right side of the road and has been related to a soil slump along the embankment of the road. This cable break has occurred on April 23 2014 and has two breaking points on a total length of 45 m. On the other side of the road a single breaking point was identified on March 2, 2013. In both cases data before and after the breaking points remain available because they are laid as a loop, only the data along the broken parts of the cable are missing.

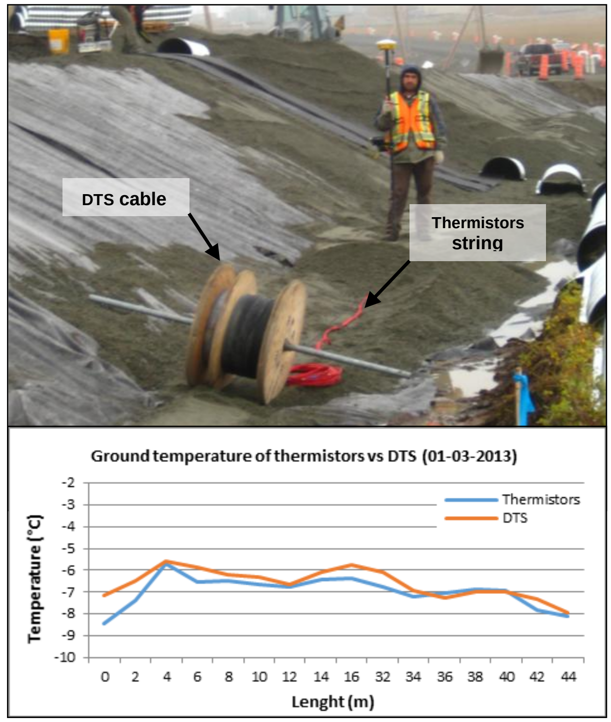

Figure 2. Top. The DTS and thermistors string installation. Bottom. Comparison of the DTS vs thermistors data along a 43 km long common section on 1er March 2013.

3.1 Preliminary interpretations

The DTS data allow the spatial and temporal analyzes at different scales. It gives the opportunity to better understand the freezing and thawing chronology along a linear infrastructure built on permafrost. According to the soil temperature data, around mid-May 2014, the whole right-hand side of this road temperatures was above 0°C while the temperatures of the left-hand side of the road were still below 0°C. Two months later, from mid-July, the left-hand side of the road records its first soil temperatures above 0°C. By mid-September 2014, the fiber optic cable along the left-hand side of the road records soil temperature data below 0°C while the other side of the road shown soil temperature data above 0°C. In total the right-hand side of the road has been ~ 6 months above 0°C while the left-hand side under the heat drain has been only one month and a half above 0°C in 2014.

Between January and October 2014, the average soil temperature of the left-hand side of the road was of -4.7°C while the average temperature of the right-hand side of the road was of -2.8°C. This significant difference of temperature between both sides of the road may be attributable to several factors, among them the geometry of ditches and culverts, the heat drain efficiency on the left side of the road or the water accumulation along the linear infrastructure. Monthly soil temperatures of data were taken on a specific part of the road, showing the difference between thermal regimes of both sides of the road. (Figure.3).

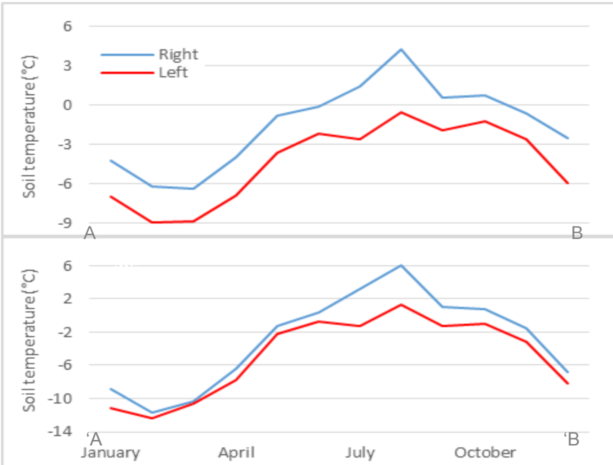

Figure 3. Monthly soil temperature data comparison between both sides of the road for two specific road sections. A,B and A' B' position are located on the Figure1

Most of the warmer areas are concentrated in topographic depressions which are filled up by water throughout the summer. During winter the same topographic depressions get filled by snow. This snow accumulation keeps the soil warmer what could explain that some parts of the road have recorded temperatures between -0.25°C and 0.25°C in late-February. In fact the hot spots observed along the road in late-February remain the same during the summer suggesting that the topographic depressions are warmed by standing water in summer, or by snow in winter keeping the soil warmer throughout the year (Figure.4).

Road sections crossed by water streams are characterized by a hasty warming. For example the soil temperature data around 0°C are recorded as soon as late-April/early-May 2014 around the major water stream crossing the road while the others soil temperature data remain below 0°C until mid-May. Similar observations were realized along smaller water seepage channels flowing throughout the embankment. According to the DTS data, the original micro topography along the road combined with water accumulation appears to play major roles in the thermal regime along this linear infrastructure built on permafrost.

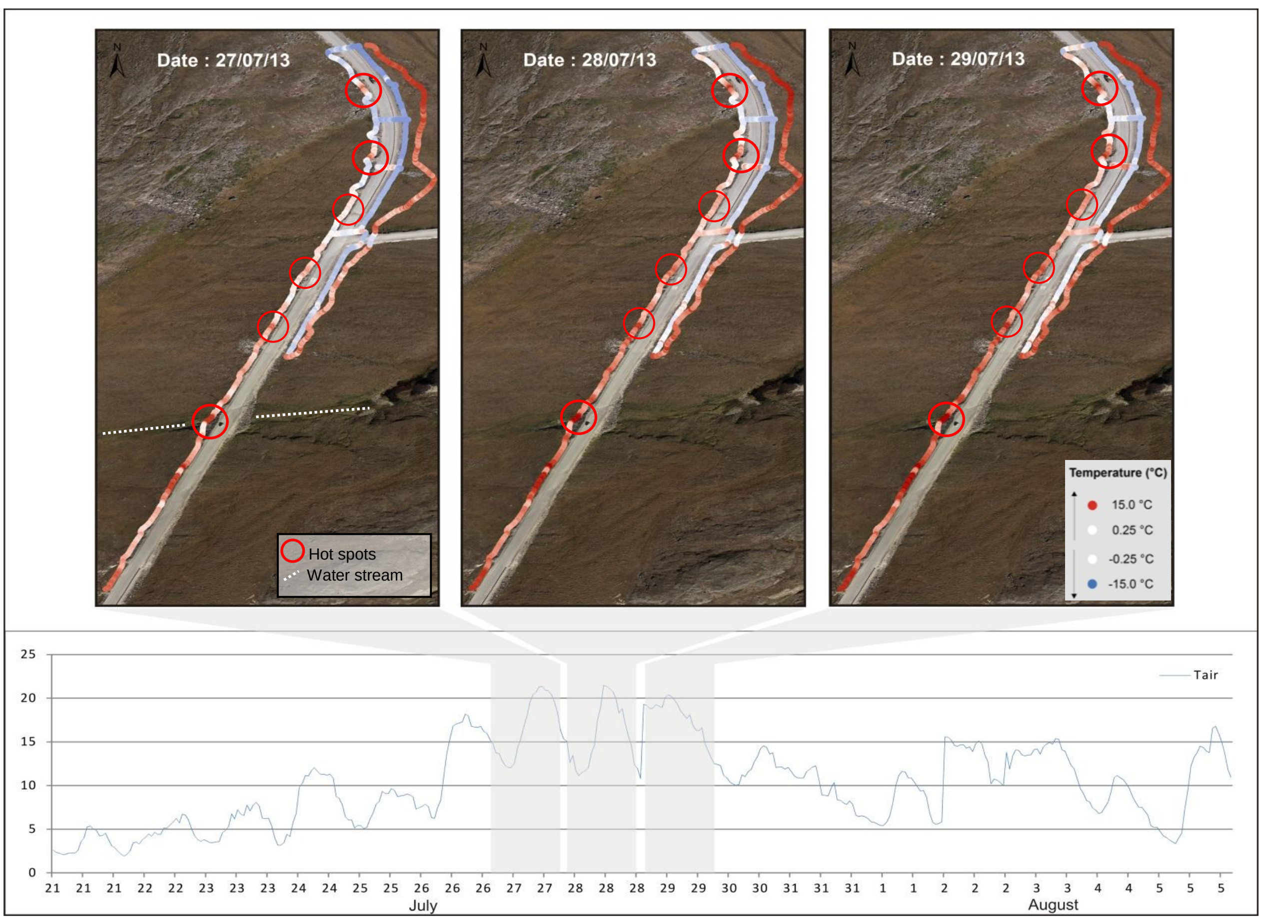

Figure 4. DTS temperature data are combined with air temperature data to show how fast the embankment of the right-hand side of the road getting warmer during a warm period compared to the left side of the road.

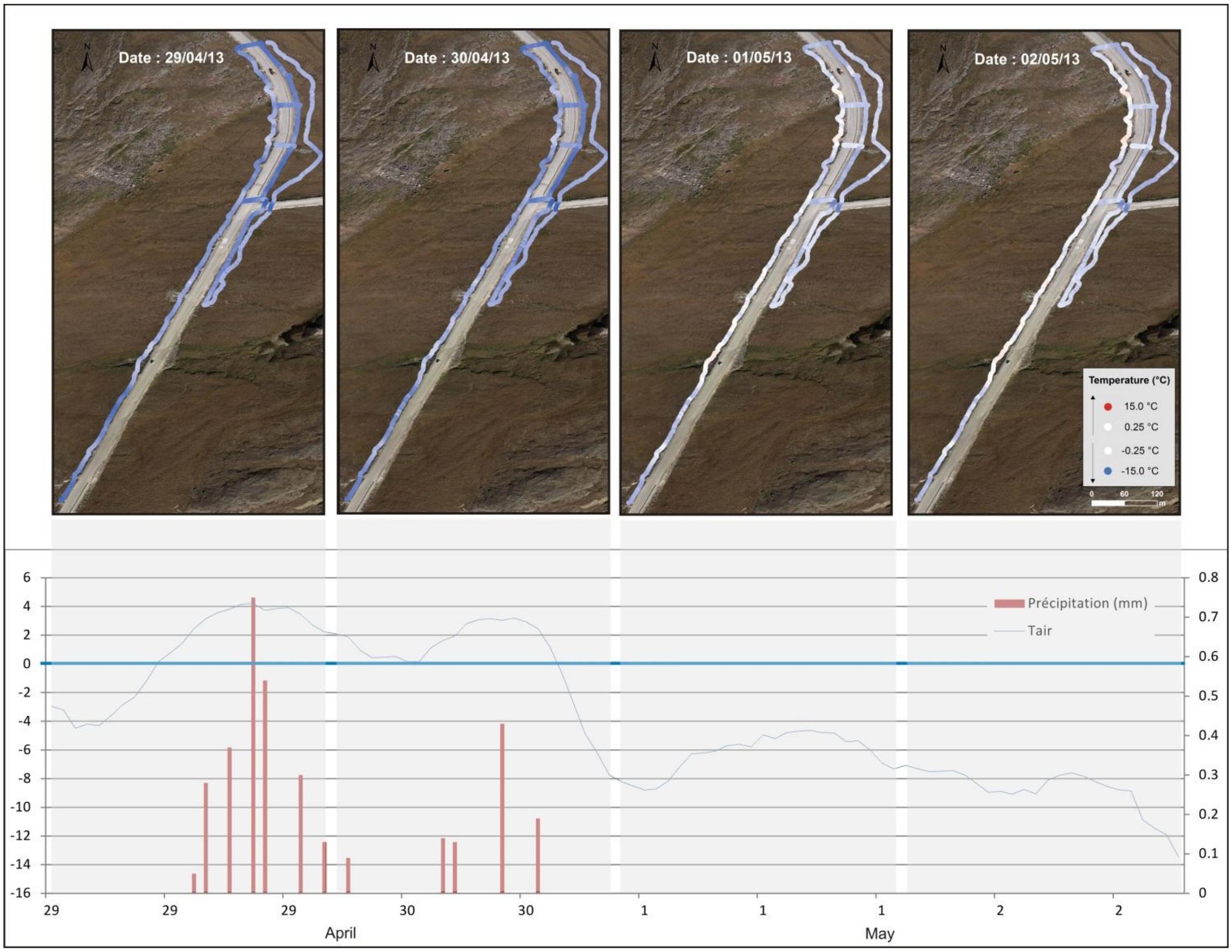

Figure 5. DTS temperature data are combined with rain and air temperature data to show the significant time lag between the air and the soil warming

By combining DTS data to air temperature and rain data from a SILA weather station in Salluit, we can analyze the ground thermal regime after rainfall periods in spring along a linear transport infrastructure. From April 29 to April 30 2013, atmospheric temperatures between 0°C and 4°C accompanied by a significant period of rain were recorded. This warm interval has been followed by a colder period taken place gradually and characterized by air temperatures below 0°C. However the temperatures recorded by the DTS exposed significant time lag between the air and the soil warming. The soil took two days to store the heat recorded on April 29 to April 30 2013 by the weather station (Figure.5). One factor is likely the accumulation of water at the base of the snowbank in the ditch.

Only a few specific places along the road have recorded instantly this warming period. These specific places can be correlated to poor drainage where small topographic depressions are filled up by water. During periods of warm temperatures, the small amount of water within the depression will get warmer faster. This process can be combined to warmer water coming from rainfall during periods of warmer temperatures. In this case the rainwater is immediately trapped in the topographic depressions along ditches, accelerating the soil warming. The same process seems to occur at the crossing of a small stream in a culvert.

CONCLUSION

The data recorded by the DTS since its implantation provided the opportunity to better understand the thermal regime along a linear infrastructure as it had never been done before. This innovative method enables us to detect problems much earlier. Furthermore we can observe the thermal transfers occurring between air and soil temperature and assess the effectiveness of engineering concepts (heat drains and new culverts and geometry of ditches design) to cool the embankment.

Various others studies can be conducted from the DTS data like the analysis of the thermal impact of localized water seepage due to improper installation of culverts or the study of the thermal impact variation along the road in function of the type of soil crossed by the road. Despite the success of DTS, several questions remain like the long term durability of the DTS cable in permafrost environments affected by polygons and frost cracking. According to the DTS obtained since 2012, it's now undeniable that the DTS technology is a very effective tool for every kind of linear infrastructure projects in permafrost environment.

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