Reducing Maintenance Requirements on Permafrost-Affected Highways: Permafrost Test Sections Along the Alaska Highway, Yukon

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ABSTRACT

A significant amount of Yukon's highway infrastructure is constructed on permafrost. In particular, the North Alaska Highway crosses extensive areas of warm, ice-rich permafrost interlaced with ice wedges. Reconstruction of the highway 10-15 years ago induced melting of the permafrost, which has continued to the present. As a result, the highway is continually subjected to severe settlements and longitudinal cracking. The current costs of maintaining the infrastructure are extremely high.

Yukon Highways and Public Works has undertaken an extensive research project aimed at finding cost-effective construction techniques to reduce permafrost thawing underneath the highway embankment. Several test sections along a 600 m length of highway were constructed in April-June 2008. Mitigation techniques being tested include: air convection embankments (ACE), heat drains, longitudinal air ducts, light-coloured aggregate surfacing, and side slope snow clearing. The test sections are instrumented with thermistors, surface temperature loggers, and weather monitoring equipment.

The mitigation techniques generally aim to keep the permafrost underlying the highway embankment frozen. If successful, the impact on road maintenance could be dramatic. Another phase of the project will involve considering new, technologically-advanced maintenance practices that may enhance road performance despite thawing permafrost.

KEYWORDS

PERMAFROST / CLIMATE / CHANGE / MAINTENANCE / THAW / STABILISATION

1 INTRODUCTION

Yukon has long stretches of highways built over warm, ice-rich permafrost that is interlaced with ice wedges. Highways built over this type of permafrost are subject to severe settlements, longitudinal cracking, potholes, and other distresses (as seen in Figure 1).

Despite spending extra money on maintenance in permafrost areas compared to non-permafrost areas, ride quality and safety standards are compromised.

a) b) c)

Figure 1 – a) Settlements on highway. b) Longitudinal cracking. c) Excavated ice wedge.

Reducing the effects of thawing permafrost on road infrastructure will require technically-advanced solutions and a change of mindset among practitioners. A team approach, involving engineers, maintenance crews, and academics, is also paramount if solutions are to be found.

Yukon Highways & Public Works (HPW) is leading an innovative research project that involves the use of non-traditional road components in an effort to stabilize the permafrost underlying a length of highway near Beaver Creek, Yukon (see Figure 2). Beaver Creek is located at 62° 22′ 59″ N, 140° 52′ 29″ W, approximately 30 km south of the Canada-United States border. Funding and research support for the project has been received by the U.S. Federal Highways Administration (through the Shakwak project), Transport Canada, Alaska University Transportation Center, Université Laval, and Public Works and Government Services Canada.

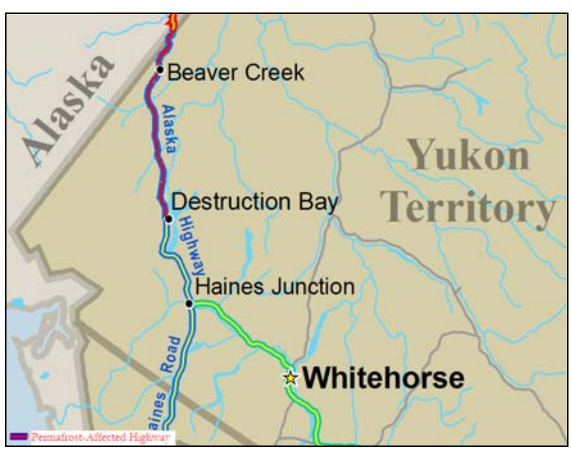

Figure 2 – Map showing permafrost-affected area (in red) on North Alaska Highway.

The mitigation techniques being tested include: air convection embankments (ACE) built with 150-300mm rock, heat drains, which involve ventilation pipes and geocomposite, longitudinal air ducts, light-coloured aggregate surfacing, grass-covered side slopes, and side slope snow clearing. Construction of snow sheds is expected to occur in early summer 2009. Each section is 50 m long. The test site is heavily instrumented, with 22 thermistor strings, 150 surface temperature loggers, and weather monitoring equipment (air temperature, snow depth, wind speed and direction).

Costs related to each mitigation technique were carefully compiled during the course of construction and are presented here. Maintenance costs for work relating to highway damage caused by permafrost are also analyzed. The costs were extracted from expenditure data from the previous three years.

If successful, implementing mitigation techniques on a larger scale will reduce maintenance expenditures. In the future, Yukon HPW also intends to pursue the use of advanced road maintenance technology to increase highway performance in permafrost areas.

2 MITIGATION TECHNIQUES

2.1 Air Convection Embankments

The concept of air convection embankments (ACE) involves building all or a portion of a road embankment with coarsely-graded rock fill. For the test sections, the rock used was a light-coloured granite and met a 150 mm to 300 mm specification. Constructing the side slopes or entire embankment out of this rock allows cold, dense air to sink into the embankment during the winter.

Three test sections were built based on the ACE concept: one involved reconstructing the entire embankment out of ACE rock and placing organics on top of the ACE on the slopes and two required the excavation and reconstruction of the side slopes. One of the side slope sections consisted of covering the rock with a 15 cm layer of organics and installing ventilation pipes in the near surface embankment material, while the other section was left uncovered and without ventilation pipes. The reason for using an organic cover is to provide some insulation value and to prevent warm wind incursions into the rock cover during the summer. Ventilation pipes were used to increase the flow of cold air underneath the organic cover and into the ACE rock. Figure 3 shows two sections near completion.

a) b)

Figure 3 – a) Full ACE embankment built; placing geotextile prior to base course. b) Finished uncovered ACE slopes section.

2.2 Heat Drains

Heat drains are an experimental method of passing cold air into an embankment. A layer of geocomposite, a synthetic egg carton-like material covered on both sides with geotextile, is placed underneath the whole embankment or in the side slopes. Pipes are attached to the geocomposite parallel to the road embankment, and connected at regular intervals to stand pipes that serve as the inlets and outlets for the cold air penetration into and the release of warm air from the embankment. Figure 4 shows two of the sections.


a)


b)

Figure 4 – a) Backfilling over geocomposite on slope heat drain section. b) View of finished heat drains with insulation section.

2.3 Longitudinal Culverts

As shown in Figure 5, longitudinal culverts were installed in the side slopes of the embankment. The culvert system utilizes 750 mm diameter high density polyethylene pipe.The system is designed to allow cold winter air to circulate through the side slope and promote heat extraction trough the chimney system.

Trenches were excavated for the culverts. They were installed in a similar manner to regular culverts. The culverts were installed approximately 0.7 m above ground water level. Figure 11 shows the longitudinal portions of the culverts as well as the inlets and outlets.


a)


b)

Figure 5 – a) Longitudinal culverts placed in trench with some heat shrinking complete (blue joints) and prior to heat shrinking and backfill. b) Finished longitudinal culverts showing inlets (horizontal pipes) and outlets (upright pipes).

2.4 Snow Clearing

In the snow clearing test section, the embankment was not modified. Rather, special maintenance techniques of clearing the snow from the entire side slopes are used throughout the winter to minimize the insulating effect of snow. Figure 6 shows the section where the snow had recently been cleared.

Figure 6 – Test section a few days after snow clearing was performed.

2.5 Grass-Covered Side Slopes

Vegetation removal during road construction has a detrimental effect on underlying permafrost. Planting grass on the side slopes is an attempt to restore some of the natural insulation effect created by natural vegetation. For the test section, organic material was spread onto the side slopes of the embankment and a native grass seed mixture was planted. Figure 7 shows the grass beginning to grow on the side slopes.

Figure 7 – Grass-covered embankment side slopes.

2.6 Light-Coloured Bituminous Surface Treatment

Increasing the albedo of a surface increases the amount of incident sunlight that is reflected. By surfacing the road with a special bituminous surface treatment (BST) using light-coloured aggregate, more sunlight should be reflected from the surface and thus less heat absorbed into the embankment. An advantage of this treatment is that it uses a conventional application process. Figure 8 shows the BST being applied.

Figure 8 – Placing the light-coloured BST.

2.7 Construction Season

Determining when to schedule construction of the test sections was one of the major decisions made during the project planning process. The most significant reason for considering winter construction was the advantage of minimizing disturbance to the permafrost, as road embankment excavations tend to initiate permafrost thawing. However, winter construction also poses significant problems. Firstly, while the permafrost would be generally preserved, the embankment would be frozen, making excavation difficult. As well, cold temperatures make it difficult to keep machinery functioning. Worker productivity suffers because of the cold and the short daylight hours. The research project involved using synthetic geocomposite and various plastic pipes that could also be more difficult to work with in extreme temperatures. These issues cast serious doubt on the quality of work that could be expected by constructing the test sections during winter months.

Utilizing the summer construction season would have alleviated many of the concerns associated with winter. Unfortunately, excavating the road embankment in warm temperatures and long daylight hours would be extremely detrimental to the temperature regime of the underlying permafrost. Since the overarching purpose of the project is to seek ways to preserve the permafrost, summer construction was not considered a viable option.

After considering each construction season, the decision was made to compromise and schedule the work to begin in early spring.

3 COST ANALYSIS

3.1 Test Section Costs

One of the main goals of the test sections project is to compare the costs of the various mitigation techniques to the costs currently incurred maintaining the highway. Consideration of the cost differences, in conjunction with any improvements in highway performance at the test sections, will form the basis for any further implementation of the mitigation techniques.

Engineering, construction, materials, and other costs were carefully tracked during the course of the project. Table 1 shows a summary of the costs related to the test sections. Each test section is 50 m long. The construction cost of the snow sheds is based on a design estimate, as the contract to build them has not yet been tendered and awarded.

Table 1 – Costs related to test section design and construction.

Test Section Description	Design Eng.	Prelim. Geotech	Materials	Construction Contract	On Site Eng.	Total
ACE – full embankment	$ 10,000	$ 3,000	$ 100,000	$ 458,000	$ 35,000	$ 605,000
ACE – slopes, covered	$ 18,000	$ 3,000	$ 61,000	$ 303,000	$ 26,000	$ 411,000
ACE – slopes, uncovered	$ 7,000	$ 3,000	$ 46,000	$ 223,000	$ 19,000	$ 297,000
Heat Drains – full embankment	$ 18,000	$ 3,000	$ 43,000	$ 226,000	$ 15,000	$ 305,000
Heat Drains – slopes	$ 10,000	$ 3,000	$ 46,000	$ 83,000	$ 7,000	$ 148,000
Heat drains – (slopes) with insulation	$ 12,000	$ 3,000	$ 66,000	$ 138,000	$ 12,000	$ 230,000
Longitudinal culverts	$ 24,000	$ 3,000	$ 59,000	$ 150,000	$ 13,000	$ 248,000
Snow Clearing	$ 2,000	$ 3,000	$ 1,000	$ 8,000	$ -	$ 14,000
Grass-covered embankment	$ 3,000	$ 3,000	$ 1,000	$ 29,000	$ 2,000	$ 37,000
Light-Coloured BST	$ 7,000	$ 3,000	$ 1,000	$ 23,000	$ 2,000	$ 34,000
Control	$ 4,000	$ 3,000	$ 1,000	$ 24,000	$ 2,000	$ 34,000
Snow sheds	$ 11,000	$ 3,000	$ 1,000	$ 181,000	$ 1,000	$ 196,000

The design engineering costs include Government of Yukon staff hours as well as time contributed by Université Laval and AUTC. Geotechnical investigation work was done the year prior to construction, and is reflected in the prelim. geotech. column. The ACE production costs reflect the differing amounts of material required for each of the three ACE sections, and include blasting, crushing, and stockpiling.

The construction contract costs reflect the monies spent actually building the test sections. They include hauling all ACE rock, 20 mm aggregate, and light-coloured aggregate to the site for the respective sections. A detour was constructed around the two full embankment sections to facilitate traffic movement. The detour construction and removal costs are incorporated into the costs for these two sections. The construction costs also include the money spent to resurface the road after construction was complete with a BST surface, matching the standard of the adjacent road sections.

Construction materials include all synthetic materials used in the project such as HDPE culverts, ventilation pipes, geocomposite, and geotextile. On site engineering covers the expense of the Government of Yukon staff who monitored construction.

The test section costs were extrapolated into a cost per kilometre over a given lifespan. The results of the analysis are in Table 2. The design costs were considered to remain constant, whether there is 50 m of highway being modified or several kilometres. The cost of snow clearing is given over fifty years, with the amount being converted to 2008 dollars. Lifespans were estimated based on predicted longevity of materials. While minor maintenance is expected over the lifespan, the systems should remain essentially intact for the duration.

As with the large scale savings estimates, the lifespan projections used in the analysis are just one possible scenario. An accurate evaluation of the longevity of each section will not be available until the test sections have been in place and observed for several years.

The cost estimates have been compiled on the basis of highway rehabilitation as opposed to new construction. Therefore, costs such as building detours around the full embankment test sections have been included, since they are not necessary if the alternative of doing no rehabilitation is chosen.

If construction is done over several kilometres, it is anticipated that there will be some cost savings due to the increased quantities. These savings are presumed to be different, with larger savings available in blasting and crushing ACE rock and lesser savings for techniques involving large quantities of synthetic materials, as the expense of procuring and shipping these materials is not expected to markedly decrease regardless of quantity.

Table 2 – Cost estimates for mitigation techniques for long-term lifespans.

Test Section Description	**Design/ Geotech Cost (50m)**	**Construction Cost (50m)**	**Operational Cost over Lifespan (per km, 5% infl/yr)**	**Life-span (yrs)**	**Large Scale Project Savings**	**Cost per year per km**
ACE – full embankment	$ 13,000	$ 592,000		50	20%	$ 190,000
ACE – slopes, covered	$ 21,000	$ 390,000		50	20%	$ 125,000
ACE – slopes, uncovered	$ 9,000	$ 288,000		50	20%	$ 92,000
Heat Drains – full embankment	$ 21,000	$ 284,000		10	10%	$ 513,000
Heat Drains – slopes	$ 13,000	$ 136,000		10	10%	$ 245,000
Heat drains – (slopes) with insulation	$ 15,000	$ 215,000		10	10%	$ 389,000
Longitudinal culverts	$ 26,000	$ 222,000		35	5%	$ 121,000
Snow Clearing	$ 4,000	$ 6,000	$2,073,000	50	15%	$ 44,000
Grass-covered embankment	$ 5,000	$ 28,000		50	5%	$ 11,000
Light-Coloured BST	$ 9,000	$ 25,000		10	0%	$ 51,000
Control	$ 7,000	$ 27,000		50	97%	$ 500
Snow sheds	$ 14,000	$ 182,000		20	15%	$ 156,000

3.2 Maintenance Costs

The cost of maintaining highway sections adversely affected by permafrost is much higher than that for non-affected areas. In order to estimate the extra money required for permafrost areas, expenditure data for two different sections of the Alaska Highway was used. Since the last major reconstruction was complete in 2005, the data set includes the three fiscal years between 2005 and 2008. All figures have been converted to 2008 dollars based on inflation rates used by engineering planning staff.

One area looked at was the section of the Alaska Highway, which is about 130 km long, in the Haines Junction maintenance area. Haines Junction is approximately 300 km south of Beaver Creek. The other area considered was the Alaska Highway in the Beaver Creek maintenance area. This section is also about 130 km long; of this length, approximately 100 km is affected by thawing permafrost.

Table 3 shows the maintenance activities that were considered for the comparison. In general, winter maintenance activities, such as snow removal and sanding, were not considered as they are not related to the presence or lack of permafrost. The average expenditures over the three years considered are also shown.

Table 3 – Average maintenance costs for Beaver Creek and Haines Junction.

Activity	Beaver Creek Average 2005-2008	Haines Junction Average 2005-2008
Surface Blading	$ 1,800	$ -
Surface Repairs	$ 45,700	$ 1,900
Dust Control/Calcium Chloride	$ 8,200	$ -
Patching with Premix	$ 328,800	$ 81,700
Clean & Reshape Ditches	$ 2,100	$ 2,800
Guard Rail/Post Maintenance	$ 1,200	$ 2,400
Sign and Post Maintenance	$ 30,800	$ 25,400
Gravel Crushing - Summer	$ 171,600	$ 137,800
BST Regular	$ 858,500	$ -
BST Patching	$ 507,700	$ 64,500
Gravel Crushing - Winter	$ 234,900	$ -
BST Sweeping	$ 47,500	$ -
Rip & Reshape/Reclaiming	$ 158,500	$ 2,800
Ditching	$ 80,000	$ 6,600
Grade Raises	$ 44,900	$ -
Berm Work	$ 4,000	$ -
Total:	**$ 2,526,200**	**$ 325,900**

The difference between the two sections is approximately $2.2 million. Based on the activities considered, this amount is the extra cost of maintaining thawing permafrost-affected highway sections. However, the Beaver Creek section is not maintained to a standard equivalent to that found in the Haines Junction section. Taking into account that the Beaver Creek area has 100 km that are disturbed by thawing permafrost, the current average cost per year per kilometre to compensate for thawing permafrost is about $22,000.

The money spent per kilometre for 2003 for the Beaver Creek section was about $36,000, a year in which about 20 km of the highway north of Beaver Creek was rehabilitated and resurfaced. Considering that the projected lifetime of BST surfaces on permafrost-affected highway is 3 years, it can be seen that the money currently allocated to maintenance work is far from sufficient to sustain the level of service that is the standard for most of Yukon's highway network. As a result, the above analysis was undertaken with the understanding that the monies allocated to maintenance are budget-dependent, not necessarily needs-dependent. If climate change predictions are correct, the highway will be subject to increased subsidence and damage from more rapidly thawing permafrost, requiring more money to be spent on maintenance.

3.3 Comparison of Mitigation Techniques and Maintenance Activities

As seen in the above analysis, the amount spent per highway kilometre on permafrost-related maintenance is $22,000. In comparison, the least-expensive mitigation technique being tested is the grass-covered embankment, which costs about $11,000 per year per kilometre over its lifetime. The uncovered ACE slopes, which have been the most effective at cooling the embankment during the first winter (2008-2009), would cost about $92,000 per year per kilometre.

The ranking of the cost per year per kilometre of the various techniques, from lowest to highest and not including the control section, is as follows:

1.	Grass-covered Embankment	$ 11,000
2.	Snow Clearing	$ 44,000
3.	Light-Coloured BST	$ 51,000
4.	ACE – slopes, uncovered	$ 92,000
5.	Longitudinal Culverts	$121,000
6.	ACE – slopes, covered	$125,000
7.	Snow Sheds	$156,000
8.	ACE – full embankment	$190,000
9.	Heat Drains – slopes	$245,000
10.	Heat Drains (slopes) with insulation	$389,000
11.	Heat Drains – full embankment	$513,000
1.	Current Maintenance Practices	$ 22,000-$36,000 and up

Based on this information, grass-covered embankments are the only technique less expensive than current maintenance practices. The lifetime projections used in the analysis are estimates only; as such the heat drains may in fact prove to be viable once several years have passed and a more accurate assessment of their longevity is available. The same logic should be applied to the other sections.

As mentioned earlier, a further option for highway rehabilitation is to develop a more specialized maintenance program for permafrost-affected highway. If successful, highways would be maintained to a better standard without necessarily addressing the underlying issue of thawing permafrost.

Cost estimates, budget availability, practicality, and performance will be the main factors in determining whether any of the mitigation techniques are implemented on a wider scale. Further implementation could range from modifying a large portion of the permafrost-affected North Alaska Highway, to focusing on critical areas such as bridge approaches and short sections of highway that are the most distressed.

4 CONCLUSIONS

The main criteria that will be used for evaluating the mitigation techniques are: effectiveness, practicality, and cost. Specialized maintenance techniques such as regular snow clearing from side slopes may be more practical than some of the other mitigation measures being tested. As well, maintenance activities typically involve minimal or no disturbance to the existing road embankment or underlying permafrost, while concepts that require excavation and rebuilding of entire embankments cause extensive disruption to temperature regimes. Full embankment ACE and heat drains may be unable to reverse the permafrost degradation induced by their construction.

Using the given estimates for lifespans and large-scale project savings, the cost per year per kilometre to implement the various techniques ranges from $11,000 for the grass-covered embankment to $513,000 for the full embankment heat drains. Currently, $22,000 per kilometre is spent on maintenance directly related to damage caused by degrading permafrost. However, this figure could be much higher if increased funding was available. Some of the sections that were relatively easy to construct, such as the light-coloured BST and the uncovered ACE slopes, are estimated to cost $51,000 and $92,000 per kilometre per year respectively.

Due to the high costs of most of the mitigation techniques, further implementation will be contingent on proof from temperature data and thermal modelling that they can considerably increase the performance of the highway and decrease the costs of permafrost-related maintenance. In addition, using advanced maintenance techniques should be considered as another component of this research project.

If this project is successful, the problems created by permafrost thawing underneath highways will be solved through a combination of non-traditional mitigation techniques and novel, advanced maintenance practices.