Rail Embankment Stabilization on Permafrost – Global Experiences

Shane M. Ferrell
E.I.T.
Civil/Railroad Designer
Hanson Professional Services
801 B. Street, Suite 400
Anchorage, AK 99501
Phone: (907) 279-1282
Fax: (907) 297-1283
Email: sferrell@hanson-inc.com

and

Pasi T. Lautala
Ph.D., P.E.
Director, Rail Transportation Program
Michigan Tech Transportation Institute
Michigan Technological University
1400 Townsend Drive
Houghton, Michigan 49931
Phone: (906) 487-3547
Fax: (906) 487-2943
Email: ptlautal@mtu.edu

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Spurred by recent concerns over rising transportation costs and the desire for increased accessibility for natural resource development, several cold climate railroad projects are currently under development around the globe. As demand for new cold climate railroads grows and the possibility of global climate change becomes more apparent, stabilization of rail transportation structures over permafrost becomes an important challenge.

A variety of engineered solutions have been developed to address the challenges of rail embankment stability. Some of the methods can be utilized both on deep seasonal frost and permafrost areas while others are mainly for rail lines on permafrost. Solutions include thermosyphon tubes; air cooled stone embankments; ventiduct embankments; shading boards and awnings; convection sheds; insulating methods such as foam boards or tire shreds; and embankment modifications such as widened shoulders and berms.

Each method has its own advantages and disadvantages and their effectiveness is often heavily dependent on local environmental conditions. Differences in soil type, temperature, precipitation and vegetation all contribute to the individuality of the site. No single engineered solution can be applied to all problem sites and the best stabilization option often appears to be a combination of solutions.

This paper will combine world-wide experiences collected during field visits in North America, Scandinavia, China and Russia and an extensive literature review to highlight the infrastructure challenges and engineered solutions in rail construction over
permafrost. It will provide some real life examples, discuss perceived advantages and disadvantages of each method, illustrate how they can be utilized in combination to increase the benefits, and provide a very basic level comparison of costs of each solution.

**Keywords:** railroad design and construction, permafrost, cold climate

**INTRODUCTION**

The construction of transportation infrastructure in cold climates has always been a challenging task. Projects such as the Trans-Siberian Railroad, Alaska Pipeline and Alaska-Canada Highway portray images of extreme conditions and rugged individuals building across wide expanses of frozen ground.

During construction of transportation infrastructure such as railroads, locations which have been thermally stable for centuries undergo a very rapid and abrupt change [1]. Due to these disruptions to the natural energy balance, permafrost soils begin to thaw, soils compress and drainage through the soil is changed. Further complicated by the potential of climate change, impacts on permafrost areas by human development are expected to be a more frequent problem. Effective countermeasures must be developed to counteract these changes, prevent soil degradation, and stabilize these sites to continue the successful development of vital transportation connections.

Recent developments, such as the demand for natural resource development, increasing accessibility to remote areas, and rising energy costs have spurred planning and
construction of cold climate rail projects worldwide. Locations such as Alaska, Canada, Scandinavia, China and Russia and are already planning or constructing, cold climate railways to efficiently move freight and passengers in these unique environments. The following sections synthesize some of the current and proposed railway operations on permafrost throughout the world and discuss different engineering solutions available to address infrastructure challenges in these environments.

**CURRENT AND PLANNED COLD CLIMATE RAILROADS IN PERMAFROST AREAS**

The majority of cold climate railroads in the world concentrate in specific geographic regions; North America, Scandinavia, Russia and China. While extensive railroad systems operate in cold climates and encounter deep seasonal frost, only a handful of rail lines are operated and maintained on permafrost.

**North America**

The majority of North American railroads operating on permafrost are located in Canada. Most Canadian lines operate in areas of deep seasonal frost, but several maintain track across permafrost. Examples of these lines include the Hudson Bay Railway, Bloom Lake Railway and the Quebec Northshore and Labrador (QNS&L) Railway. Hudson Bay Railway provides an interesting example, as it is one of the only rail lines in the North America where significant engineered solutions were applied to address the permafrost issues.
The Alaska Railroad also operates short segments of track that traverse permafrost soils, such as area around Gold Stream Siding near Fairbanks. The Alaska Railroad is currently developing two new extensions to its network and one of them, the Northern Rail Extension, is expected to cross several short sections of permafrost soils along its 80 mile route.

Another North American permafrost line will be the Baffin Railway. The line is planned for Baffin Island in northern Canada and will be built entirely on continuous permafrost. The line will serve to connect a proposed iron mine to a new port and loading facility. With a forecasted freight tonnage of 20 MGT annually, the design incorporates a special cold weather steel rail to prevent rail breakage. This added design feature is due to the extreme freezing temperatures found on the island. Construction is expected to begin in 2010 and be completed by 2014 [2].

Scandinavia

While Finland, Sweden and Norway all operate and maintain thousands of miles of railroads in areas of deep seasonal frost, only a small portion of Scandinavian railroads operate on permafrost. Majority of these short sections are on discontinuous permafrost along an iron ore railway, “Malmbanan”, in Northern Sweden / Norway. According to the engineers, challenges caused by the permafrost sections are fairly limited and are handled through annual maintenance, if necessary [3].
Russia

Russia has perhaps the most extensive rail network on top of the permafrost in the world, mainly in Northern and Eastern Siberia. Some of the world’s most comprehensive permafrost research has been conducted in Russia, including several studies focusing exclusively on railroads. Examples of the lines include Trans-Siberian Railway which has many segments across discontinuous permafrost and the Baikal-Amur Railway, 75% of which is build across permafrost. Additionally, the line from Sirgut to Min (in the Tindra area) is built on approximately 20 feet of permafrost on top of bedrock and additional permafrost layers.

The Baikal-Amur Railway has experienced significant challenges over time, such as development of ice dams along the line (Figure 1) and it is estimated that to date, the cost of maintenance has exceed the construction costs of the line [4].

![Image of ice dam on Baikal-Amur Railway Line](image)

**Figure 1: Ice Dam on Baikal-Amur Railway Line**

*(Courtesy of Professor Bellazeroff, Siberian State Railway University, Novosibirsk, Russia)*
Russia is also planning several new railway lines. One of which is the Tyva Railway which will connect Kuragino with Kyzyl for mining related operations. This rail link will allow access to one of the world’s largest deposits of coking coal and bring economic activity to an isolated portion of Russia. The construction is expected to start in 2010 for completion in 2014 and the project will be a partnership that utilizes both public and private funding sources [6]. Unfortunately the authors haven’t been able to define whether this line will cross permafrost areas.

China
In China, the majority of cold climate railroad activities are focused around the Qingzang (or Qinghai-Tibet) Railway stretching nearly 1,200 miles from Xining to Lhasa. The final segment of the railway connecting Golmud to Lhasa was opened in 2006 and the railway began operations shortly after. Approximately 300 miles of the new rail line was built across continuous and discontinuous permafrost. In addition to extensive permafrost soils, over 80% of the Golmud to Lhasa route is located over 13,000 feet above sea level with a maximum elevation of nearly 16,500 feet. The construction of Qingzang Railway has positioned China on the forefront of permafrost engineering.

Several engineered solutions (often combinations of solutions) have been developed and utilized in the attempt to reduce the potential for permafrost degradation. Many of these methods target permafrost preservation and according to updates on monitoring efforts, the foundation soils have performed as designed, or at some sections have actually raised the permafrost table above original state [7].
China has recently expanded its cold climate rail network in Qinghai area by constructing an 87 mile long coal-transport railway from Reshui to Muli with approximately 60% of the line underlain by permafrost [7]. The line opened for testing in late 2009 and various engineered solutions were also adapted along this line to maintain permafrost soils.

**CHALLENGES**

Several challenges must be overcome when constructing or operating railroads over permafrost, but one of the most critical ones is embankment deformation. Some of the main causes of embankment deformation stems from the disturbance of native soils during construction activities. Soils that have been undisturbed for centuries have essentially reached a state of thermal equilibrium – the thermal forces affecting the soils have been balanced over time, allowing the state of the soil to remain constant.

Construction activities, such as clearing, grubbing and earthwork impart many unnatural forces upon the soil and environment as each natural surface feature has its own role in maintaining energy balance. When features such as vegetative cover is stripped or altered, changes to precipitation factors and solar absorption become obvious and previously frozen soils often begin to thaw and consolidate (Table 1).

The placement of a heavy soil embankment, instead of the natural surface cover, leads into development of a significantly different thermal profile and thermal equilibrium is disrupted. The result is thawing, settlements and increased stress on the subgrade soils.
Table 1: Surface Features and Their role in Energy Transfer

<table>
<thead>
<tr>
<th>Environmental Feature</th>
<th>Site Function</th>
</tr>
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<tbody>
<tr>
<td>Vegetation</td>
<td>Protection from surface radiation, influences convection currents and moisture flow.</td>
</tr>
<tr>
<td>Precipitation/Water &amp; Ice</td>
<td>Directly related to site drainage and moisture flow. Phase change energy is generated through this feature as well. Soil freezing also alters soil matrix structure.</td>
</tr>
<tr>
<td>Soil Type</td>
<td>Fine grained soils can retain or absorb water, creating saturated soil pockets and reducing bearing capacity. Coarse grained soils freely drain water and change little in volumetric size when frozen.</td>
</tr>
<tr>
<td>Solar Influence</td>
<td>Impacts the amount of radiation present at a given site. High altitudes and low latitudes result in more exposure to solar radiation.</td>
</tr>
<tr>
<td>Wind Currents</td>
<td>Influences convective cooling of the surface. Can provide cooling or warming influence depending on the temperature of the current.</td>
</tr>
</tbody>
</table>

With the new development and construction of cold climate rail lines, many of these geotechnical issues are expected to become significant concerns and long term embankment stabilization is emerging as a critical priority. The possibility of warming global climates may further exacerbate the ground conditions beneath these rail lines.

Historically, embankments constructed across permafrost have depended upon the frozen ground to provide bearing capacity for the infrastructure. These stiff permafrost soils perform well in carrying the loads imparted by the infrastructure and railroad traffic. However, if stabilization methods are not utilized, these soils often begin to thaw and degrade and the bearing capacity of the subgrade is reduced, leading to embankment settlements and distortions.
Ultimately, maintenance resources, track time and financial capital must be diverted from other projects to address these failures. As embankments and ballast sections deform, tracks may be out of the tolerance for their operational speed, leading to possible slow orders and delays. Maintenance crews may also slow or stop trains as they repair and adjust distorted track alignments. If solutions can be identified to minimize or eliminate these embankment distortions, fewer maintenance disruptions will allow higher operational speeds and increased line capacity.

Permafrost degradation can often be reduced to manageable levels, or maintained in a frozen state by using cooling solutions. Thermal balance should be considered by designers and engineers and the appropriate response will depend largely on the local conditions. The acceptability of operational delays and slow orders, design preferences of the engineer or project owners, and costs are major considerations to account for when making stabilization decisions. One end of the scale is to aggressively use selected engineered solutions to minimize the annual degradation, while the other end of the scale is to minimize capital expense and address all challenges through annual maintenance activities. The next sections present a review of the most commonly used engineered stabilization solutions for permafrost construction.

ENGINEERED SOLUTIONS

There are many engineered cooling solutions available to stabilize embankment soils. In this paper, the solutions have been classified using a descending order of perceived thermal effects from “active cooling” to “passive cooling” (Figure 2). Active cooling
methods are perceived to have the greatest ability to actively remove heat from the embankment and are listed near the top of the list. Methods which do not actively remove heat from the embankment, but function to reduce heat absorption, are categorized as passive cooling.

![Figure 1: Active Cooling vs. Passive Cooling](image)

**Thermosyphons**

Thermosyphons are used where the frozen state of the soil must be maintained. (Figure 3) A thermosyphon is a sealed tube which is pressurized and filled with a low boiling point liquid such as Freon, ammonia or carbon dioxide [8]. As air temperature drops below that of the embankment, the tube uses evaporation and condensation of the liquid to remove heat from the embankment and dissipate it into the atmosphere.
Thermosyphons are effective in utilizing the cold temperatures of winter to cool the embankments while guarding against the warming effect of the summer months. The liquid in the tubes will only boil if the soil is warmer than the air so during warmer summer months heat transfer is essentially stopped [9,10].

Areas of high-ice permafrost and transitional areas between permafrost zones and non-frozen ground may see the greatest benefit from these devices [11, 12]. Some example locations where thermosyphons have been utilized include Hudson Bay Railway in Canada and Qingzang Railway in China.

Thermosyphons are best utilized for high risk sites with unstable permafrost. They are expected to stabilize soils and refreeze thawed soils. Damage during transport and
operation is very detrimental as depressurization or obstruction of the cooling fins will render these devices useless.

**Ventiduct Embankments**

Ventiduct embankments typically utilize a traditional soil embankment with the inclusion of pipes placed across the embankment. These pipes serve as “air culverts” allowing air to pass through the embankment center and draw heat out from the soil (Figure 4).

As the temperatures rise in summer months, the warm air flowing through the pipes can increase heat absorption within the embankment [13]. Therefore, many ventiduct systems have been equipped with shutter systems which allow the pipes to be sealed during warm periods in order to minimize air flow (Figure 4).

![Ventiduct Embankment with shutters](image)

**Figure 4: Ventiduct Embankment with shutters [13]**

One such system, located on a highway in Alaska utilizes dampers which are manually opened during winter and closed during summer [10]. Other applications of the dampers include automatic systems which can be linked to nearby weather stations for accurate
temperature readings [13, 14]. In addition to Alaska, this method has been utilized along Qingzang Railway.

Ventiduct embankments require natural wind currents to remove heat from the embankment. Sufficient drainage along with minimal frost and snow accumulation suit these systems best as air flow must be maintained through the pipes. Differential settlements can also reduce air flow blockage due to snow or debris may also increase maintenance potential and reduce effectiveness.

**Air Cooled Stone Embankments**

There are multiple types of air cooled stone embankments. Most embankments are built either from block stones or crushed rock. Block stone embankments utilize large aggregates roughly 8-12 inches in diameter while crushed rock embankments use smaller aggregates 3-4 inches in diameter. Both embankment types have been used in various configurations (Figure 5), depending on available air currents, solar influence and snowfall.

![Figure 5: Rock Embankment Configurations [27]](image-url)
Stone embankments have been used at locations where rail lines cross warm permafrost and the long term stability of the embankment has been in danger [11, 15, 16]. These embankments use poorly graded aggregates to create pore space within the embankment. This porosity allows air to penetrate into the structure and by means of natural convection remove heat from the subgrade [17, 18].

Due to the low thermal conductivity of the air and the small contact area of the stones, the rock layers function as a thermal insulating barrier, limiting heat flow into the embankment. This insulating effect causes a large heat loss in the winter with limited heat gain during the summer. The resulting net heat loss improves embankment stability when compared to a traditional embankment. [11, 19]

An interesting application of air cooled embankments was revealed in Russia where local scientists developed two designs utilizing blocks of frozen clay to protect the embankments (Figure 6). The solutions included: 1) the use of large crushed rock and frozen clay blocks inside the embankment to allow for controlled drainage and 2) the creation of a clay wedge to allow for runoff of snow and water into the ditch without intrusion into the embankment.

In the second solution, the top of the embankment was constructed with impermeable layers to prevent water infiltration, but allow air flow through the embankment to cool the structure. According to local scientists, these solutions were developed as “low-cost alternatives”, as it was cost prohibitive to transport the needed amounts of large
aggregates to the construction areas. Clay was found locally and broken to large, frozen blocks during winter months [5].

Figure 6: Frozen Clay Blocks Used for Embankment Construction in Russia

(Courtesy of Dr. Vladimir Lonskaya, Federal Research Transportation Institute, Omsk, Russia)

Stone embankments utilize natural wind currents and depend upon reliable air flow to remove accumulated embankment heat. Plugging due to snow or fines as well as the potential for differential settlements should be considered when deciding on this method. Availability of large aggregates is also a key factor although the Russian example shows engineering alternatives may be available.
Awnings/Shading Boards

Awnings / shading boards function in several ways, but primarily by reducing the influence of solar radiation on the embankment. In addition to the solar energy reduction, they also reduce water infiltration, minimize snow accumulation (which increases frost depth) and increase convection cooling by utilizing airflow to remove heat from the embankment surface [20]

These structures can be constructed of several types of material, such as a rigid wood or metal frame with soft canvas sides, or as a stiff composite structure placed on the embankment shoulders. (Figures 7, 8) Embankment awnings can also be constructed as standalone structures, or used in areas of deep cuts or recesses as a canopy above the track [20]. The canopy cover can help to keep costs down by removing the requirement for a rigid frame.

![Figure 7: Railways Embankment Awnings [20]](image)
Shading boards and awnings are best placed in locations with significant solar radiation influence or where water infiltration is expected to be a significant factor for permafrost degradation. Damage due to natural or manmade occurrences such as wind damage or vandalism may reduce their effectiveness and increase maintenance costs.

**Expanded Polystyrene Insulation**

Subgrade and embankment insulation layers can be used as standalone measures (Figure 9), but are typically used in conjunction with other stabilization. The objective is to increase the thermal resistance of the embankment through the use of insulation. During winter months when the embankment is warmer than the air, the insulating layer provides a “heat preservation” effect which decreases heat release. In the summer months when the embankment is colder than the ambient air, the insulation provides a “cold preservation” effect which limits heat absorption into the soil [21]. This reduces large temperature shifts and creates a more uniform temperature distribution for other cooling methods to work more effectively.
In general, polystyrene provides good strength properties, resists water absorption and can survive mechanical damage such as cracks and indentations which may occur due to ballast and train loadings [24]. However, tests suggest that during the 50 year life cycle of an insulated embankment, the thermal protection of insulation alone may not be sufficient. As an example, Zhi estimates that given climate warming models, permafrost thaw will still occur beneath insulated embankments along the Qingzang Railway [23].

Insulation layers are best used in areas with moderate to high external heat influx and can also be used to minimize the require construction depth of the embankment. Water absorption issues and mechanical damage can decrease life span and effectiveness so these factors should be mitigated whenever feasible.

**Dry Bridges**

The dry bridge method is the most drastic stabilization method and has been used previously in locations in which settlement and thaw were considered unavoidable, even with the utilization of engineered solutions. Extremely thaw unstable soils, poor soil
conditions and areas where extremely stable track are required are likely candidates for this method. Bridges utilize piles driven deep into the soils so stability and settlements are not anticipated.

Construction of the dry bridge must be completed prior to the placement of the rail, the same as a traditional bridge. Dry bridges have been utilized at some of the most challenging locations along the Qingzang Railway and Muli Railway (Figure 10).

![Figure 10. Er’a’ga dry bridge on Muli Railway, China [22]](image)

Dry bridges are the most radical and also the most expensive of the stabilization techniques. These bridges should only be used in extremely high risk sites where stable track is an absolute requirement. Potential failure modes include differential settlements of the columns or damage due to disasters such as earthquakes, landslides or derailments. Due to their significant costs, these bridges are anticipated to be used rarely and only when absolutely necessary.
SUMMARY OF STABILIZATION METHODS

Below is a table which summarizes the typical objectives (or outcomes), potential disadvantages and expected cost of each of the engineered solutions presented. The cost estimate was developed in August of 2009 for a site specific case study in Alaska and cost data presented are rough approximations for Alaska conditions. These costs have been inflated to account for the scarcity of aggregates and the difficulty of shipping needed construction materials to a remote site along the Alaska Railroad mainline. While the provided comparison is by no means comprehensive guide to selecting most appropriate engineered solutions, it can be the first step to identify the alternatives.

<table>
<thead>
<tr>
<th>Engineered Solution</th>
<th>Expected Outcome</th>
<th>Potential Drawbacks</th>
<th>Cost ($/100 track feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermosyphons</td>
<td>High risk sites, unstable permafrost, useful for transitional zones</td>
<td>Damage during transport or installation, obstruction of fins, maintenance potential</td>
<td>$27,500-$30,800</td>
</tr>
<tr>
<td>Ventiducts</td>
<td>Minimize differential settlements, reduce internal temperature of embankment</td>
<td>Blockage due to snow or debris, minimized performance due to settlements, water ponding, maintenance potential</td>
<td>$9,800- PVC $16,500- Concrete $23,750- Metal</td>
</tr>
<tr>
<td>Block Stone Embankments</td>
<td>Increase convection cooling of entire embankment, increased full width embankment stability</td>
<td>Plugging due to snow or fines, settlements risk</td>
<td>$44,800</td>
</tr>
<tr>
<td>Crushed Rock Revetments</td>
<td>Convection cooling of shoulders, stability of shoulder sections</td>
<td>Warming in center of embankment with cooling of shoulders (differential settlement), plugging due to snow or fines</td>
<td>$12,000</td>
</tr>
<tr>
<td>Awning/Shading Board</td>
<td>Reduce solar radiation, minimize</td>
<td>Damage due to natural or manmade occurrences,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water infiltration, improve convection cooling</td>
<td>Maintenance potential</td>
<td>No Data</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------------------------------------------</td>
<td>------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td><strong>Extruded Polystyrene</strong></td>
<td>Minimize heat influx into soil, reduce frost penetration depth, minimize construction depth</td>
<td>Water absorption, mechanical damage, decreasing insulation performance</td>
<td>$2,300</td>
</tr>
<tr>
<td><strong>Dry Bridge</strong></td>
<td>Ensure stability during permafrost degradation, eliminates settlements and thaw consolidation</td>
<td>Differential settlements of columns, damages due to natural or manmade occurrences</td>
<td>$1,040,000</td>
</tr>
</tbody>
</table>

**CONCLUSIONS AND NEXT STEPS**

With the increasing interest in mineral and natural resource development in the far north, cold climate railroads will play an important role in their viability and long term operational goals. Many of these railroads will be focused primarily on heavy haul freight operations and will require heavy axle loadings and a robust design. Due to the inherent challenges in building and operating railroads on permafrost, cost effective solutions to reduce the potential for embankment deterioration due to permafrost thawing is of high priority. Alternatives presented in this report should be taken into consideration during engineering and design. Decisions should be made between anticipated reduction in long term maintenance and the potentially high initial capital investment, if such methods are applied.

This paper has introduced some of the most common engineered solutions to address challenges caused by thawing permafrost and several examples of their use throughout the globe. The relevance of these topics is expected to increase, as natural resource development reaches more areas that located on permafrost. If global climate change
becomes more prevalent, it may increase the challenges by changing climate conditions in locations typically not affected by warming or cooling trends. As these situations develop, the importance of understanding alternative methods to mitigate the challenges increases.

It was recognized during the research that the current trend of railway construction on permafrost extends throughout the globe and challenges faced by North American railroads are similar to problems faced by other railroads around the world. While the most effective methods for mitigation are dictated by the local conditions, most of the alternatives are the same throughout the world. Therefore, global cooperation should be improved to facilitate the development and distribution of innovative solutions. With a greater combined effort to combat these settlements and track disturbance issues, different perspectives are leveraged and better solutions may be developed.
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