LAPIN AMK
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INTRODUCTION TO PERMAFROST ENGINEERING

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Tämän opinnäytetyön tavoitteena on tutkia kirjallisuusselvityksen avulla ikiroutaa, ikirouta-alueella tapahtuvaa rakentamista sekä yleisiä haasteita ikiroutaan liittyen. Tutkimus toteutettiin keräämällä tietoa alan raporteista, koulutusoppaista, konferenssijulkaisuista sekä kirjoista. Työssä perehdytään ikiroutaan, ikiroudan muodostumiseen, palsoihin, rakentamisen perusteisiin ja rakentamiseen pohjoisessa.

Maapallolla ikiroutaa esiintyy noin 20 prosentilla maapinta-alasta. Suurin osa ikiroudasta löytyy pohjoisesta, arktisilta alueilta. Vuosien varrella insinöörit ovat rakentaneet rakennuksia, teitä, junaraiteita ja lentokenttiä ikiroudan päälle. Rakennusmetodeja on ollut useita. Usein nämä hankkeet ovat kuitenkin epäonnistuneet, ja rakennelmat ovat lyhyessä ajassa muuttuneet käyttökelvottomiksi ikiroudan arvaamattomuuden vuoksi. Jää on substanssina hyvin herkkä ulkoisille muutoksille, ja pienistäkin muutoksista voi seurata peruuttamattomia vaikutuksia jäiseen maakerrokseen. Yksi näistä ulkoisista muutoksista on lämpötila. Ilmaston lämpeneminen näkyy erityisesti arktisilla alueilla. Vuosituhansia ikiroudassa olleet alueet sulavat, ja ympäristöt muuttuvat. Insinöörityön osalta tämä tarkoittaa entistä vaativampaa ja tarkempaa suunnitteluprosessia. Yksi suurimmista vaikeuksista on päätös siitä, kannattaako rakennushankkeen alla oleva maa pitää jäässä vai sulattaa ja luoda kokonaan uusi, kestävä perusta.

Suomessa ikiroutaa esiintyy lähinnä Tunturi-Lapissa ja Metsä-Lapin pohjoisosissa, erityisesti palsasoilla, jotka keskittyvät Käsivarren ja Utsjoen koivuvyöhykkeelle. Palsasoilla esiintyy ikiroutaisia palsakumpuja, jotka antavat Suomen luonnolle omalaatuisen leiman. Ikirouta tekee näistä soista haastavia rakennuskohteita.

Asiasanat Permafrost, Palsa, Foundation Design, Active Method, Passive Method

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Abstract of Thesis

Technology, Communications
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The objective of this thesis was to study permafrost engineering in the form of a literature review. More specifically, the aim was to collect information about the relevance of permafrost to engineers working in the Arctic. This thesis also provides an explanation of topics such as the formation of permafrost, palsas, foundation designs, active and passive methods of foundation design, and permafrost in Finland.

The study was conducted by collecting information and data through reports, guide books, interviews, conference publications, proceedings, newspapers and lectures. The principal research method was to become familiar with the subject through many works discussing the topic of permafrost. Essential theory and information on permafrost engineering was then collected and compiled into one writing.

Nearly 20 percent of the world’s land area is underlain by permafrost. Most of the affected land areas can be found in the northern hemisphere, in the Arctic. Throughout the years, civil engineers have built buildings, roads, railways and airfields on ground underlain by permafrost. There are multiple design paths and methods of constructing on frozen soil. Unfortunately, many of these construction projects have failed and the structures have become unusable due to the unstable nature of permafrost. Ice as a substance is extremely vulnerable to thermal changes, which are now escalating due to ongoing climate change. Previously frozen land areas are thawing, causing irreversible changes to the surrounding habitat. The increasingly unstable permafrost areas force engineers to apply their practical and theoretical knowledge in order to successfully construct a structure on ground that is underlain by permafrost.

Key words Permafrost, Palsa, Foundation Design, Active Method, Passive Method

CONTENTS

FOREWORD

My interest in permafrost engineering jumpstarted during my study abroad in University of Alaska Fairbanks. I would like to thank Professors Yuri Shur and John P. Zarling for inspiring my future aspirations in my professional and academic careers. I would also like to thank Roadscanners Oy and especially CEO Timo Saarenketo for giving me the opportunity to work amongst permafrost engineering sites in northern Finland.

1 INTRODUCTION

Permafrost, or perennially frozen ground, is a widespread issue in the Arctic that requires engineers to use and come up with various ingenious techniques to utilize the frozen earth beneath their feet. People have always had a certain vision and a sense of great accomplished to be able to occupy and build in even the most barren environments. To be able to construct on frozen ground is an example of extreme engineering feats that have been closely researched and practiced.

As globalization and population growth pushes us further into the last frontiers, water and cold temperatures give birth to a whole different levels of related engineering problems. Nevertheless, problems are made to be solved and engineers have found more or less successful ways to construct roads, bridges, railroads, airfields, and buildings on frozen ground and ground that is affected by frost heave during winter.

To add to the equation of challenging foundations that permafrost presents, the progressive global warming occurring today is not making the job any easier for arctic engineers. Annual soil temperatures keep rising, causing previously frozen earth to start thawing. This thawing of soil leads to new problems related to construction in the Arctic, as engineers have to battle to keep the ground frozen or unfrozen.

Roads and highways have been some of the first big engineering feats in the Arctic. Modern day highway engineering knowledge in the Arctic has had to literally work its way through the trenches. The history of road construction in the Arctic gives a great insight into permafrost and the related engineering problems.

The purpose of this thesis is to give a clear and understandable introduction to what permafrost is, where it can be found and what kind of problems it presents to civil engineers and other engineers working in the Arctic. Permafrost engineering as a topic is vast. The goal of this literature review is to gather essential information on permafrost engineering into one writing. Information and data was collected through reports, guide books, interviews, lectures, conference publications, proceedings, and newspaper articles. The information gathered is the knowledge scientists and engineers have access to today. This thesis also brings forth the topic of global warming and its effects on the Arctic and engineers that work with permafrost. Thawing of permafrost caused by climate change is a major issue for civil engineers but also for affected flora and fauna. It is essential that the ongoing changes are researched and taken into account.

2 PERMAFROST

2.1 Definition of Permafrost

Permafrost is ground or soil that has been frozen for two years or longer (Ferrians, Kachadoorian & Greene 1969). The definition of permafrost is based almost exclusively on the temperature of the ground or soil. Thus, when the definition demands the soil to have remained frozen for two or more years, frozen refers to 0°C or colder (Zarling 2015). The temperature boundary that starkly determines whether the rock or soil material is frozen is necessary due to the fact that moisture is not always visible in a sample. This means that if ice is visible, it is easy to determine that the sample is frozen. On the other hand, if no ice is visible, the sample can still be frozen and thus definable through temperature measurement.

2.2 Relevance to Engineering

Permafrost is a large scale engineering problem. This is solely due to the fact that almost 20% of the land area of the world is under the influence of permafrost (Ferrians, Kachadoorian & Greene 1969). Even though approximately one fifth of the land area of the world is underlain by permafrost, most of it occurs in the northern hemisphere, as seen in Figure 1.

Additionally, problems have begun to emerge as previously frozen areas thaw. Global warming that has been progressing rapidly has led to thaw settlement at unexpected levels. Drastic changes in temperature have forced engineers around the world to act in numerous different ways to control and manage the new challenges. The thawing of previously frozen areas also affect the flora and fauna that are found in the changing areas.

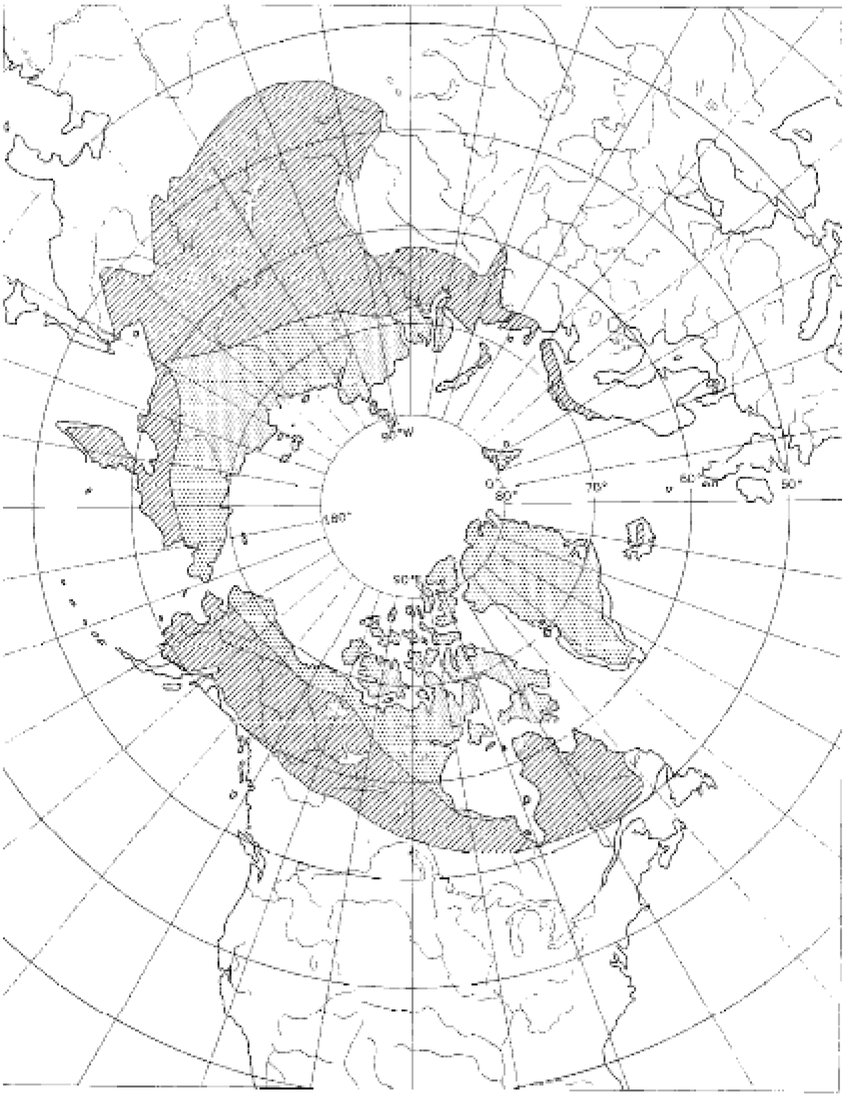


Figure 1. Extent of Permafrost Zones in Northern Hemisphere (Ferrians, Kachadoorian & Greene 1969)

2.3 Permafrost Zones

The arctic region of the northern hemisphere can be defined in various ways, depending upon the field of science and the topic at hand. When discussing permafrost engineering, it is often thought to be the area that is underlain by continuous, discontinuous or sporadic permafrost. Within the continuous zone, permafrost can be found in almost “all directions”. Like the name might suggest, in the discontinuous zone, permafrost can be found but there are also permafrost-free areas. These permafrost-free areas increase the more you travel south from the continuous zone towards lower latitudes. What controls the manifestation of permafrost is largely related to the temperature variations that come from climatic patterns, and differences in latitude and altitude. Sporadic discontinuous permafrost describes individual areas of permafrost that are surrounded by unfrozen ground. Russian research defines it as permafrost underlying 5 to 30 percent of the exposed land surface (van Everdingen 1998). Sporadic discontinuous permafrost is relevant in this undergraduate thesis because Finland has scattered land areas underlain with permafrost that can be described as sporadic permafrost. All of the permafrost sites are located above the Arctic Circle, close to the northern border of Finland. Most of the permafrost research in the world has been produced in the U.S.S.R (Now Russia), together with Canada and the United States of America. (Zarling 2015.)

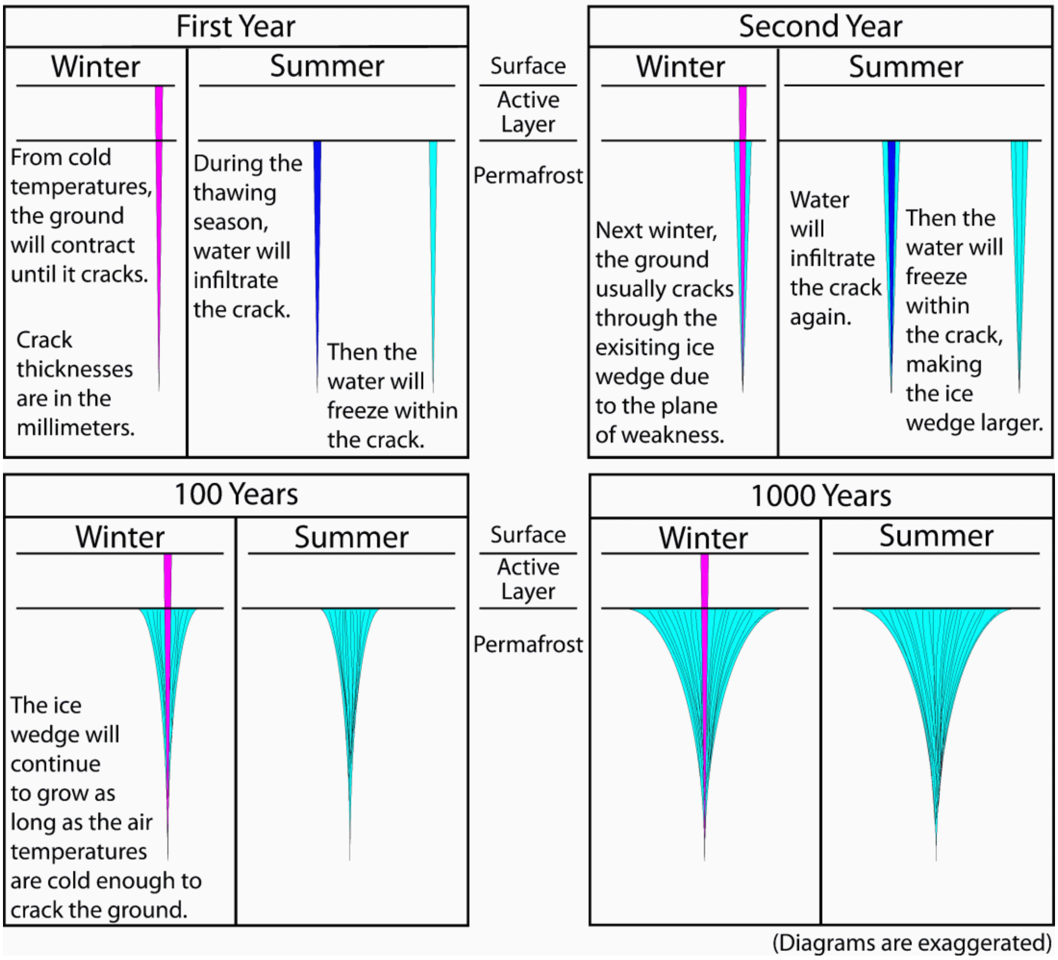
3 METHODS OF PERMAFROST FORMATION

3.1 Epigenetic and Syngenetic Permafrost

When speaking of permafrost formation, there are two principal methods. The first is epigenesis and the second method is syngenetic permafrost formation. Epigenetic permafrost forms through epigenesis, where the permafrost forms by freezing of soil or rock downwards from the bottom of the active layer after deposition of the soil sequence has ended. The time lag between soil accumulation and its perennial freezing can be thousands or millions of years. Syngenetic permafrost formation takes place simultaneously with deposition of the soil material, and freezing follows deposition in the same direction. In syngenetic permafrost formation there are two moving fronts: the sedimentation front on the ground surface, and the permafrost front at the bottom of the active layer. Simply put, epigenetic permafrost grows downward, and syngenetic permafrost grows upward. It is good to note that there is a possibility to have permafrost that is the combination of both methods, in which both methods grow at the same time in the same space or profile. (Shur & Osterkamp 2007.)

3.2 Differences Between Epigenetic and Syngenetic Permafrost

Perhaps the clearest difference between epigenetic and syngenetic permafrost is that they form in opposite directions. Nevertheless, there are very distinct and important differences in the processes of the two methods. These differences govern the formation of the permafrost. Syngenetic permafrost is nearly always ice-rich, holding ice-wedges in it that penetrate its entire strata. Within syngenetic permafrost, it is possible to find ice-wedges as deep as 50m (some found in Siberia). Syngenetic permafrost soil has typically high organic content, but the cryogenic structure of the soil is not dependant on the geological origin of the soil. Ground water can only be found in the active layer; thus, no intrusive ice can be found in syngenetic permafrost. On the other hand, epigenetic permafrost has various formations of ice lenses and layers of sediments. As mentioned earlier, the sediment layers are typically well consolidated and if high ice content is found, it is limited to the upper permafrost. Unlike in syngenetic permafrost, the origin of the soil affects the ice content in epigenetic permafrost. The process of ice-wedge formation can be seen in Figure 2. Additionally, epigenetic ice-wedges usually grow in width, while syngenetic ice-wedges grow in length (one wedge on top of another). Figure 3 illustrates the differences between the ice-wedges. (Shur & Osterkamp 2007.)



From cold temperatures, the ground will contract until it cracks.

Crack thicknesses are in the millimeters.

During the thawing season, water will infiltrate the crack.

Then the water will freeze within the crack.

Next winter, the ground usually cracks through the exisiting ice wedge due to the plane of weakness.

Water will infiltrate the crack again.

Then the water will freeze within the crack, making the ice wedge larger.

The ice wedge will continue to grow as long as the air temperatures are cold enough to crack the ground.

(Diagrams are exaggerated)

Figure 2. Formation of Ice-Wedges (Cold Regions Research and Engineering Laboratory 2012)

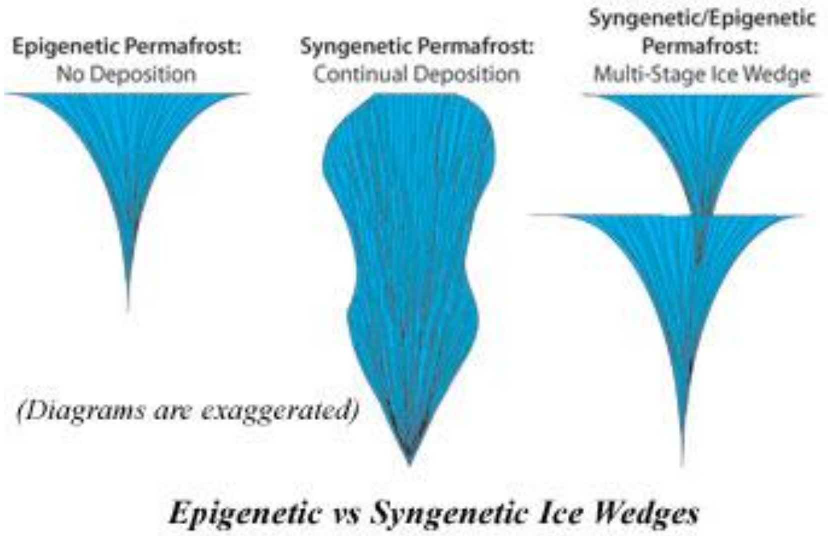


Figure 3. Difference Between Epigenetic and Syngenetic Permafrost Ice Wedges (Cold Regions Research and Engineering Laboratory 2012)

3.3 Ground Ice Distribution and its Effects

Permafrost can have various combinations of soil type, water content and ice distribution, which together determine the thaw stability of the permafrost. Figure 4 below (Nidowcz, Osterkamp & Shur 2000, 243-254) shows the different classifications of ground ice distributions. Out of the different permafrost types, only I.1 is thaw stable and the others are thaw susceptible. The thaw susceptible permafrost types are likely to have great differential settlement, ice-wedges and other problems that affect construction works and others.

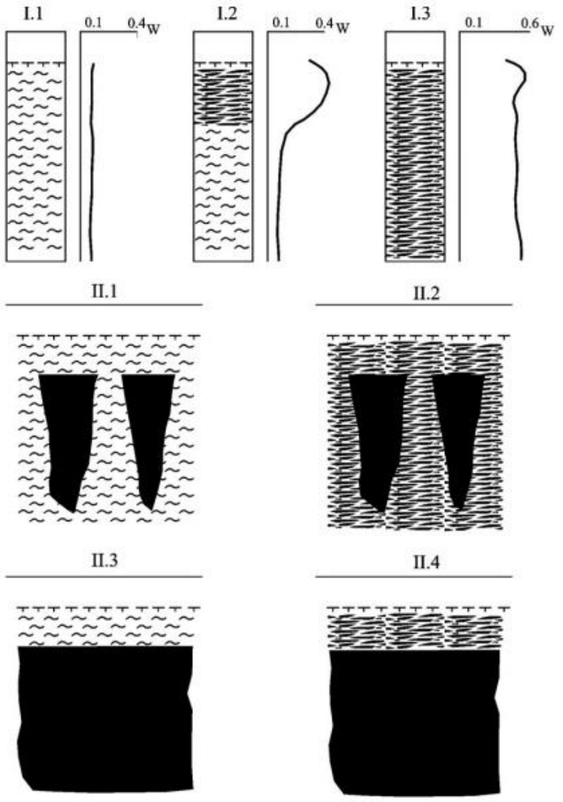


Figure 1. Distribution of ground ice in soil (black is ice). ***Distribution type I*** *(permafrost with suspended ice): I.1: Low ice content permafrost; permafrost is thaw stable; I.2: Ice-rich upper part of permafrost with low ice content below; I.3: Ice-rich permafrost.* ***Distribution type II*** *(permafrost with massive and suspended ice): II.1: Ice-wedges and mineral soil of low ice content above the ice-wedges; II.2: Ice-wedges with ice-rich soil above the ice-wedges; II.3: Sheet ice with mineral soil of low ice content above the ice; II.4: Sheet ice with ice-rich mineral soil above the ice.*

Figure 4. Distribution of Ground Ice in Soil (Nidowcz, Osterkamp & Shur 2000)

3.4 Palsas

Palsas are peaty permafrost mounds that rise from the ground 0.5m to 10m in height, and averaging 2m in diameter. The diameter has been documented to exceed up to 100m. Palsas usually originate from wetlands such as peat bogs (see Figure 5).

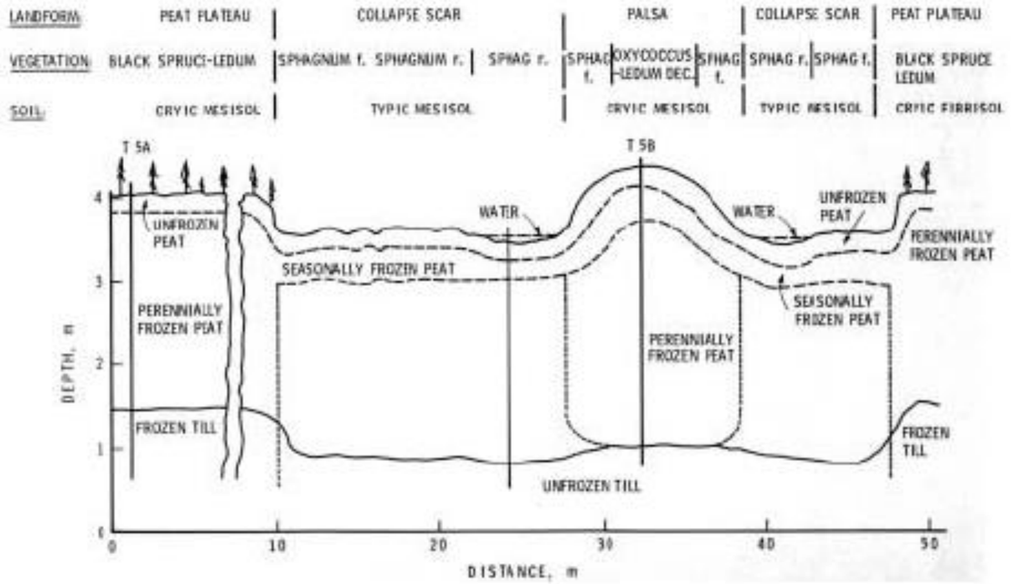


Figure 5. Cross Section of a Peat Plateau with a Palsa (van Everdingen 1998)

Peat plays an important role in the construction of palsas. Ice segregation in mineral soil beneath peat is what feeds the growth of palsas. As mentioned earlier, palsas occur in the sporadic discontinuous permafrost zones. Palsa mounds possess a core of ice, but can also be of alternating layers of segregated ice and mineral material (van Everdingen 1998). Due to the fact that palsas usually occur in subarctic lowlands underlain with peat and excess moisture, a number of these mounds can give a distinctive look to the surrounding environment, similar to ice wedge polygons as seen in Figure 6.

In more detail, palsa mounds occur in quite specific circumstances. Palsas require a cold winter climate where the average temperature is below 0°C, low rainfall and uneven snow cover due to strong winds. What could be described as the basic factor that the palsa ice core needs in order to survive, is the insulating property of dry peat. (Seppälä 1997, 87-96.) The thickness of the peat found in the palsa mires is usually at least one metre which is what palsas need as a minimum thickness in order to form the ice core. In palsa mires the peat allows cold temperatures to reach deep into the saturated and frozen peat, and when early spring and summer comes, the surface layer of the peat dries rapidly and protects the ice core found inside the mound against thawing. (Seppälä 1997, 87-96.) Palsas accent from the mire as the ice core inside grows. It is possible for a palsa mound to collapse if the peat layer on the surface erodes and cracks. The erosion and cracking of the peat layer results in the thawing of the ice core inside the palsa. If the conditions are favourable, palsas occur naturally and their development takes hundreds of years. (Suomen Ympäristökeskus 2010.)

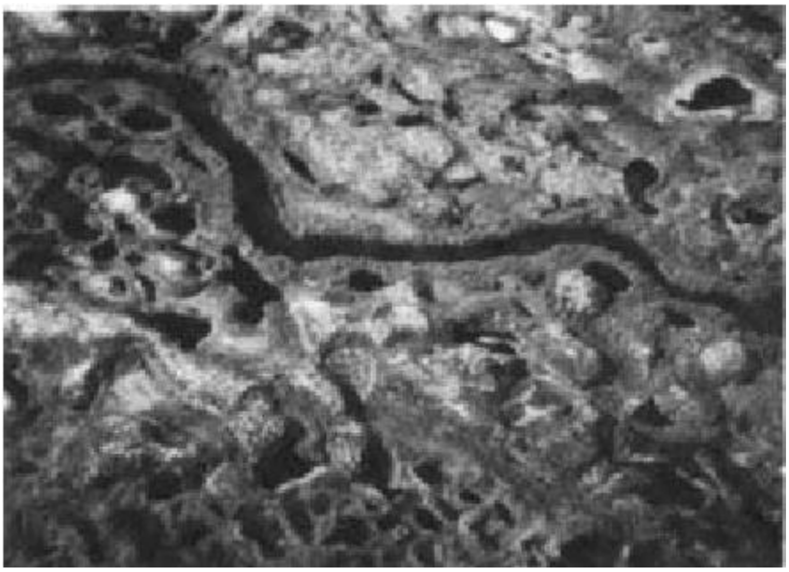


Figure 6. Palsa Complex (Seguin)

4 PERMAFROST RELATED PROBLEMS ON ROADWAYS

4.1 Modes of Distress

Within cold region countries, it is apparent that roads have number of problems that do not occur in warmer climates. The pavement performance of roads can be divided into three different categories of distress that occur in cold climate regions: distortion and faulting, cracking, and disintegration and wear (Rooney & Vinson 1996, acording to Vinson, Zomerman, Berg & Tomita 1989, 4). The following descriptions of the three different modes of distress will give more insight into the permafrost related problems that were also found in the three different cases that will be presented in this thesis.

Today, the most common driving surface that is used in road projects is the flexible AC (Asphalt-Concrete) pavement. AC pavement has become a somewhat standard as it provides a good surface for increased traffic volumes compared to gravel roads. Gravel roads that were maintained by blading and grading presented problems such as longitudinal and transverse cracking, embankment instability, seasonal frost heaving and differential subsidence in ice-rich permafrost. Additionally, gravel roads have loose particles that often result in traffic-induced dust clouds which then reduce the visibility of drivers. On the other hand, it is important to note that even after the introduction of better driving surfaces like the flexible AC pavement, the above mentioned distress failures still take place. Driving surfaces have advanced but so have the maintenance costs compared to gravel roads. This puts a lot of emphasis on the importance of planning and designing. Often the initial costs of constructing can seem high, but if the initial planning and designing is not done correctly, the future maintenance costs can lead to unbearable maintenance costs or just general abandonment (as seen in Figure 7). (Rooney & Vinson 1996, 4-12.)

Figure 7. Severe Differential Subsidence on an Abandoned Gravel Road (Ferrians Kachadoorian & Greene, 1969)

4.2 Distortion and Faulting

Movement (distortion) of roads and the resulting faulting is undoubtedly the clearest and most visual indication of roadway deformation. Distortion and faulting is usually caused by frost heave, thaw degradation of permafrost and thaw weakening in the active layer. As mentioned earlier, the causality of these occur in the subarctic and the arctic regions. (Rooney & Vinson 1996, 5.)

Clear examples of pavement deformation are longitudinal and transverse cracking, differential subsidence (result of thawing permafrost and seasonal frost heave) and other frost action movements (see Figures 7, 8, 9 and 10).

Figure 8. Typical Gravel Road Surface with Oncoming Vehicle Generating a Dust Cloud Behind It (Rooney & Vinson 1996, 6)

Figure 9. Example of Longitudinal and Transverse Cracking due to Snow Insulated Embankments (Critical Depth of Snow Surpassed) (Rooney & Vinson 1996, 6)

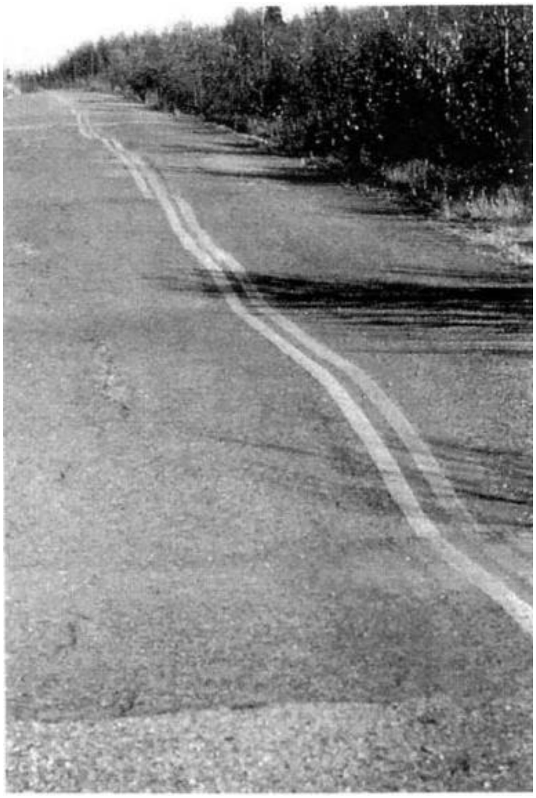


Figure 10. Surface Deformation due to Seasonal Frost Heaving and Permafrost Thawing (Rooney & Vinson 1996, 7)

Frost heave, one of the main causes of roadway distortion, is generated by the combination of access to water, frost susceptible soil and cold temperatures (three W's: winter, water and wick) (Rice, 1975). To reduce distortion and faulting caused by frost heave, it is generally recognized that the mitigation or elimination of one or more of these factors must be done. Removing frost susceptible soils to reduce wicking can often be impractical. Thus engineers today favor the use of insulation to mitigate cold temperatures. Especially when discussing roadway engineering, the most important factor to be considered is drainage (Belz, 2015). Drainage is focused upon to get rid of water as much as possible, which is damaging to roadways in warm and cold regions alike. With limiting cold temperatures through insulation and water supplies through good drainage, engineers have at least some tools to battle against frost heave. (Rooney & Vinson 1996, 4-12.)

Municipal utilities such as wastewater pipes, clean water pipes, rainwater pipes, district heating pipes, cables, drains, and culverts should be avoided beneath pavements with frost susceptible subgrades. These previously mentioned utilities often experience frost heave and jacking. A common problem that occurs with utilities and roadways is that insulation is put on top of the buried utility. This localized insulation often causes a transition between the adjacent unprotected highly frost susceptible soil. What this means is that the road section with the buried utility will have clear heaving along the uninsulated section, which can lead to ponding (gathering of water), general settlement (uncomfortable drop in road for drivers), and other roadway distortions (see Figure 11.). Consequently, the biggest distortions (differential movements) are related to the different soil frost heave responses. If it is not localized insulation causing transitional heaving, it can be due to different soil material in backfill of a culvert trench and the adjacent soil underlying the pavement. Frost susceptible soil with adjacent non-frost susceptible soil can have severe differential movement even in a short period of time (1 year), but this can be mitigated by trying to have identical backfill soil and adjacent soil underlying the pavement. (Rooney & Vinson 1996, 4-12.)

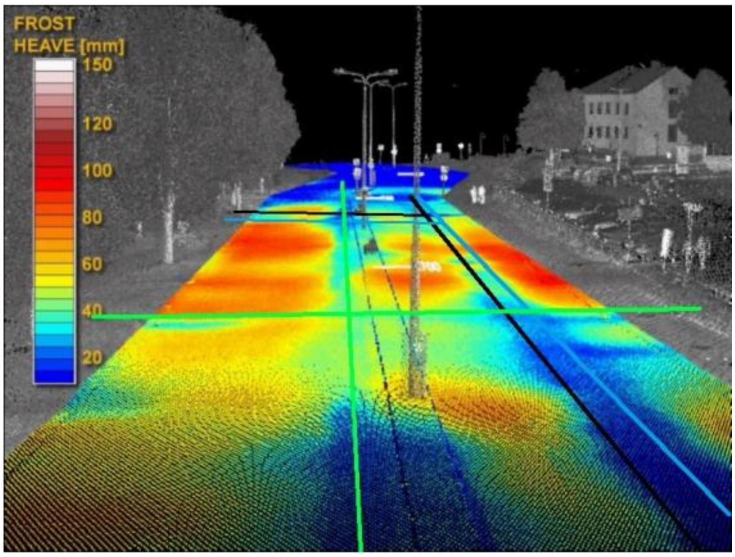


Figure 11. Frost Heaving in Relationship to Insulated Municipal Utilities (Rytilahti 2016)

As mentioned earlier in this section, along with frost heave the thaw weakening of the pavement structure can lead to pavement deterioration and general faulting. This deterioration occurs under repeated loads (such as large vehicles) through the process of cumulative damage. Repeated cycles of thawing and freezing weakens the subgrade under the pavement which in turn begins to bow under repeated loads (soil settles under the pavement). An example of this is a bus stop with settlement due to the repeated load of busses, as seen in Figure 12.

Figure 12. Roadway Faulting by a Bus Stop (Rytilahti 2016)

4.3 Cracking

Cracking, which was briefly discussed in the previous section about roadway distortions, is the most common problem that occurs on roads in subarctic and arctic regions. Roads can undergo both traffic and non-traffic induced cracking. In other words, cracking can occur due to cumulative damage caused by vehicles (traffic/load) or due to other reasons such as thermal changes. (Rooney & Vinson 1996, 4-12.)

Transverse cracking is usually caused by the contraction of the entire pavement which happens due to cold temperatures. These transverse cracks are not only limited to the pavement level, but can also go through to the subgrade under the pavement. Other reason for transverse cracking is that the tensile strength of the AC pavement fails under very low temperatures. In other words, the bonds between the pavement particles are pulled apart. In summary, thermal cracking is caused by these two different distress mechanics and is non-traffic related. (Rooney & Vinson 1996, 4-12.)

An example of a traffic related cracking is fatigue failure of the pavement. Fatigue failure refers to the phenomenon where the pavement is repeatedly bent by the traffic load which then in turn cracks the pavement surface. (Rooney & Vinson 1996, 4-12.)

Lastly, reflection cracks are, as the name suggests, a reflection of a crack in the underlying pavement. Some roads are maintained by stripping the top layer of the pavement and then placing a new overlay on top. This is done to restore a smooth wearing surface on a distressed roadway. The problem with this is that the underlying problem that causes the cracks is not taken care of. When the pavement under the new overlay distorts horizontally and/or vertically, the cracks beneath the overlay are then expressed to the top. The road would then show the exact same problems that it had previously. Putting an overlay on an already distressed roadway is just an aesthetic fix for a short duration. The only complete fix for reflection cracks is to remove the old underlying pavement completely. (Rooney & Vinson 1996, 4-12.)

4.4 Disintegration and Wear

Disintegration is usually a result of faulty mix design and poor construction. These two can result in an inadequate mix of asphalt cement, poor compaction of the mix, overheating of the mix, or under heating during the construction phase. (Rooney & Vinson 1996, 4-12.)

If the mix is not compacted well during construction, water can get into the voids. Water inside the voids can then begin to break the adhesion between the aggregate and the asphalt cement.

The above mentioned disintegration mechanics then lead to the breaking up of the pavement. The pavement begins to turn into small, loose particles. As with most roadway distress problems, once you have a disintegrating section of a road, it will begin to grow cumulatively. Furthermore, studded tires contribute to the increase of road wear. Along with studded tires, snow plowing and other snow removal methods shorten the life of a road.

Pavement studies in Finland have shown that if pavement contained weathered products, damage was expected. The components had the tendency to absorb water which in turn formed a small layer above the mineral pebbles. As foreseeable, once the freezing cycle began, the water froze inside the voids giving access to traffic-induced damage to the weakened pavement. In some cases, a hydrophobic liquid was inserted to the surface to prevent water from entering the voids (Kinosita 1989, 733-748). Studies have also concluded unanimously that the freeze-thaw cycle in arctic and sub-arctic regions plays a big role in the damage and disintegration of roads. Disintegration and weathering of roads is often a result of many factors, like the combination of freeze-thaw mechanism and traffic induced stress, as shown in the study of “Highway 955 Kotakumpu-Nilivaara” in 1983 Kittilä, Finland. (Saarenketo & Nieminen 1989, 709-720.)

5 FOUNDATION DESIGNS

5.1 Introduction to Foundations

When constructing on areas underlain by permafrost, a common theme rises related to the design process. Designing the construction is a long process and selecting the right choice of methods is done when all factors have been evaluated. If not done thoroughly, costs can be high. Not only engineering factors need to be taken into account, but also economic factors. One of the biggest mistakes that can be made is by basing a decision solely on estimated construction costs. Factors like foundation construction scheduling, planning the correct building site, drainage, fill, ground thermal situation, foundation type (deep or shallow), anticipated service life and others need to be taken into consideration as well. What this means is that detailed site investigations and careful office evaluations must be made before anything is started. The constructor should also be diligent in choosing the correct designers, who have previous experience and sound engineering judgment when deciding design and construction of foundations. Everything that is done carefully before construction will ultimately determine whether it will perform adequately in the end. “A poor man can’t afford cheap things” is an old saying that is definitely valid when considering construction on ground that is underlain by permafrost. (Davison, et al. 1981, 247-343.)

Structures in arctic and subarctic regions should be constructed at locations with clean, granular, and non-frost susceptible materials. Whenever possible, these materials should also be free of ground ice. When these materials thaw, they usually stay quite stable and are not affected much by frost heave and settlement. This is of course in comparison to fine-textured materials. (Unified Facilities Criteria 2004.)

5.2 Design Approach

There are two main design approaches if the ground material is thaw unstable. Note that these two principal methods to foundation design are only considered in permafrost areas. However, before diving deeper into the thaw unstable design approaches, if the foundation materials are thaw stable, the frozen condition of the material can be overlooked and construction can be done according to conventional foundation designs. To return to the subject, the two thaw unstable design approaches are the “Passive Method” and the “Active Method”. (Davison et al. 1981, 247-343.)

In cold permafrost regions, the “Passive Method” is most commonly used and desirable when constructing permanent structures. In its essence, the “Passive Method” attempts to maintain the foundation materials in a frozen state. If it is not possible to avoid thaw degradation and a change in thermal regime is evident, the second “Active Method” needs to be considered. Unlike “Passive Method”, it attempts to get rid of the problem or let the degradation happen in any case. So the “Active Method” can be divided into two processes, either remove and replace the thaw susceptible materials with better materials, or construct the designed structure so that it can withstand the possible settlement during its service life. Below, Figure 13 displays the different paths when considering the right construction method for buildings and what design approach should be chosen in most cases. (Davison et al. 1981, 247-343.)

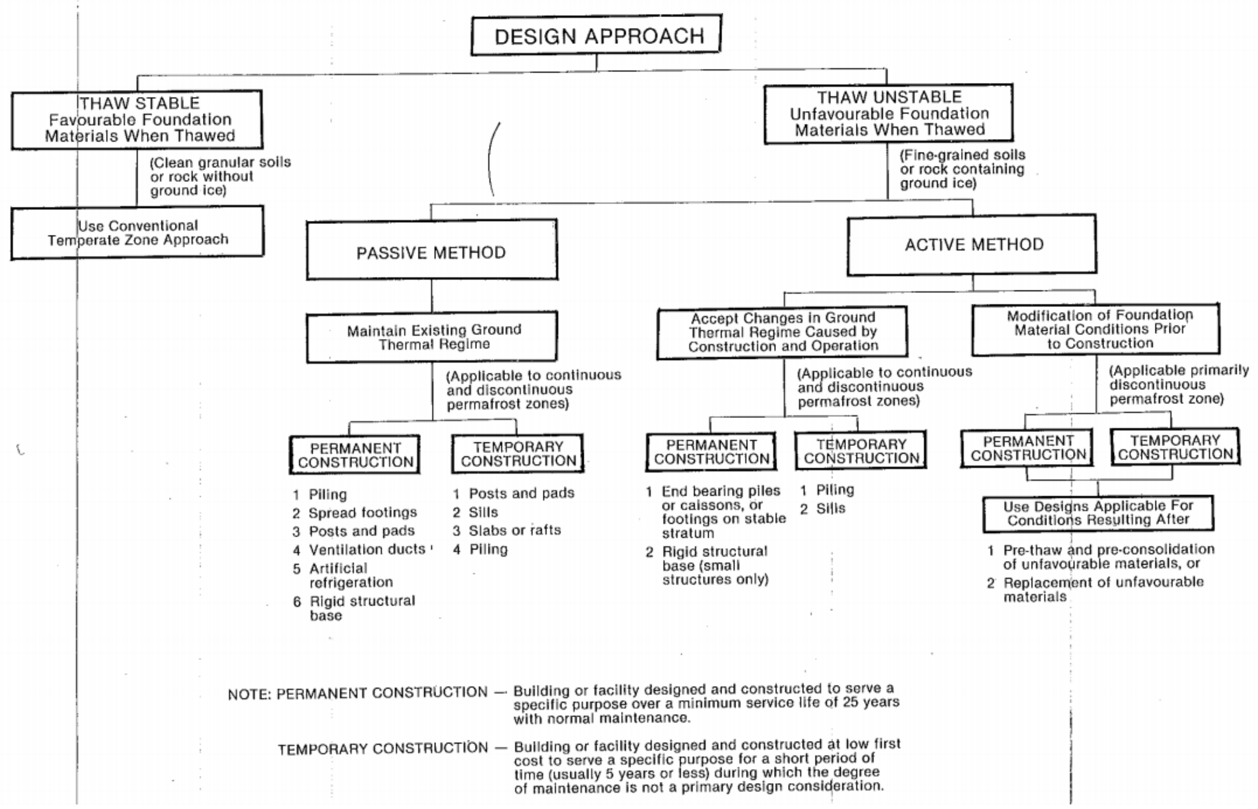


Figure 13. Design Approaches When Constructing Buildings or Similar Structures on Permafrost Areas (Davison et al. 1981)

When constructing roads and pipelines, it is almost impossible to use just one method. Thus, in such cases where methods change and transitions happen between the two, special attention needs to be given to the development area. (Shur 2015b, 80-111.)

5.3 Passive Method

It is important to remember when choosing the passive method that it is used when the underlying foundation soils are hard frozen in their natural state. A general guide would be that if the permafrost temperature is below -4°C, “Passive Method” is recommended (Shur 2015b, 80-111). When this condition is met, it is usually economically practical to keep the ground in its frozen state. This unfortunately is almost exclusively limited to the continuous permafrost zone. Keeping the ground at a hard frozen state or even at a frozen condition in the southern discontinuous permafrost zone can be difficult, or even impossible when looking at sporadic areas. Of course, all sites and locations are unique, and thorough investigation and planning will determine whether maintaining the frozen condition through the “Passive Method” is feasible. However, if the mean ground temperature is warmer than -3°C, and the ground material is wished to maintain at a frozen state, the design approach should be thoroughly thought through. (Davison et al. 1981, 247-343.)

When you have a foundation on ground that is underlain by permafrost, the thermal relationship between the two can be quite complicated. Through conductive heat transfer, the underlying permafrost can and will eventually begin to thaw and end in settlement. This is something to be taken into account when constructing structures that are heated, but permafrost degradation can happen due to various other reasons as well. These reasons are all thermal related, in which enough heat is somehow transferred into the surrounding ground surface. Solar radiation, underground utilities, groundwater flow and surface drainage can all disturb the ground surface and cause changes to the thermal equilibrium. The most commonly used methods of keeping the ground frozen within a certain thermal range are insulation (Figure 14) and ventilation (natural or artificial ventilation). Less common but also effective, artificial cooling of the soil is used to maintain the frozen state (Figure 15).

Figure 14. Insulation Beneath Roadway Embankment (Zarling 2015)

Figure 15. Thermosyphons in China to Maintain the Frozen Condition Below a Roadway Embankment (Shur 2015d)

5.4 Active Method

Unlike the “Passive Method”, “Active Method” can be used when it is no longer economical to keep the ground material in its frozen state. It can also be used if the soil is permeable and can be thawed. A general guide is that the active method should only be used if the foundations are built on a stable base such as well compacted, dense, thaw-stable soil or bedrock. In short, it is recommended in situations where the soil is relatively thaw stable. (Shur 2015b, 80-111.) “Active Method” is often used in sporadic discontinuous permafrost areas where the permafrost can be found in small areas and can be pre-thawed. (Davison et al. 1981, 247-343.)

Choosing “Active Method” as the design approach requires the designer to consider whether the foundation soil is allowed to thaw after construction (whether the structure can take the thaw settlement in tolerable limits) or if thawing of the soil done prior to construction. Decisions should be based much on the estimates of probable thawing, shear strength and the total expected settlement. (Davison et al. 1981, 247-343.)

In the case that the total settlement exceeds what is tolerable, it is then possible to use heating methods such as steam points (see Figure 16), gas heaters or electrical heaters to thaw the foundation soil. After preconstruction thawing with the previously mentioned heat sources, the thaw susceptible soil should either be compacted or removed. If removed, it can be excavated through the means of explosives or rippers and then replaced with non-frost susceptible material. Again, it is important that the foundation is well compacted and stable enough to hold the structure. Drainage should not be forgotten at any point. (Davison et al. 1981, 247-343.)

Figure 16. Example of Pre-Thawing Localized Permafrost with Steam Points (Zarling 2015)

Pihlainen (1951) recommends the following thawing methods as seen from his chart for construction techniques on sporadic permafrost areas: steam thawing and removal of soil, thawing by solar radiation and removal of soil, use of explosives and removal of soil, and hydraulic stripping of soil for large areas. It seems that thawing methods are quite limited and these seem to be the most common methods even today.

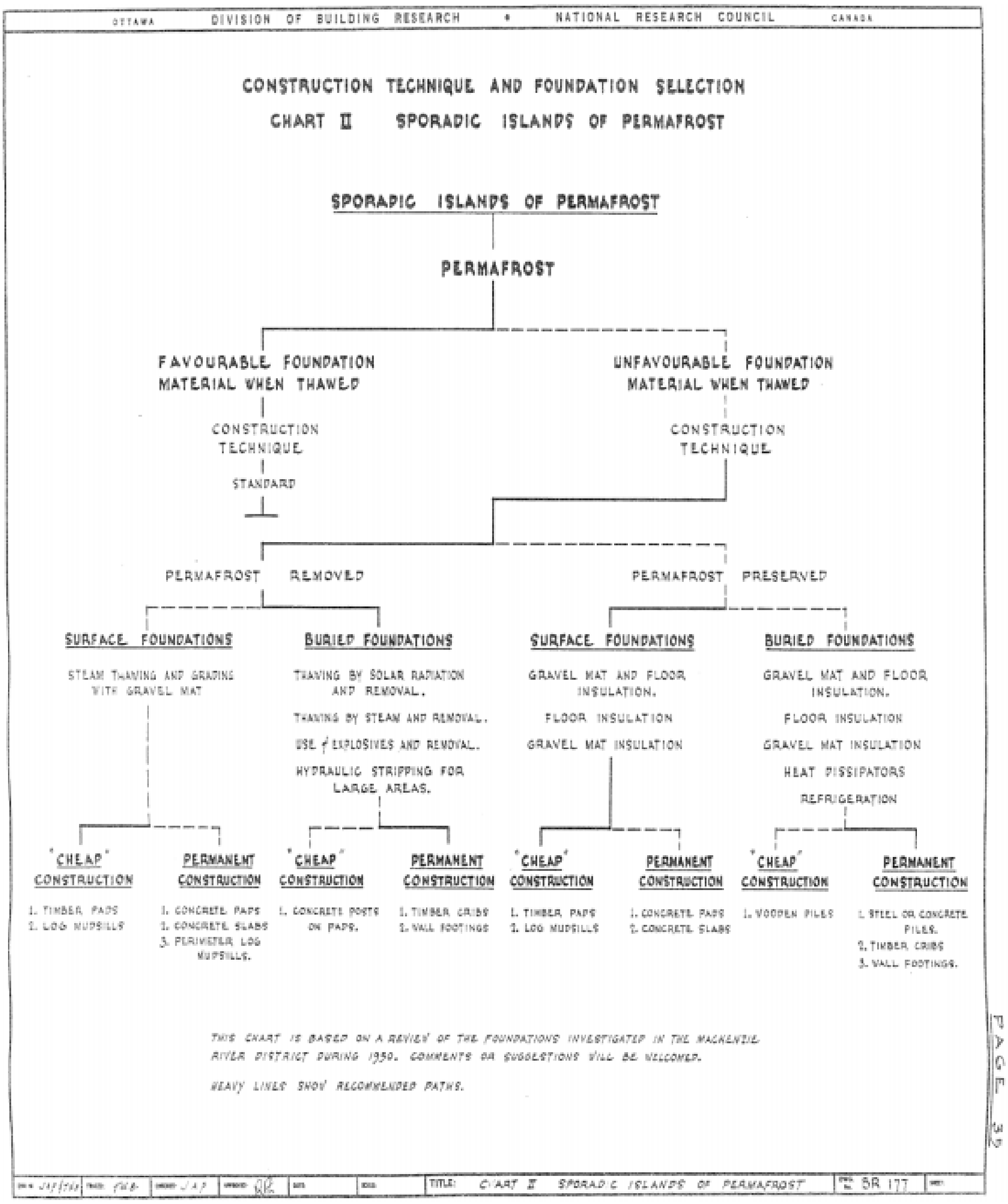


Figure 17. Construction Techniques on Sporadic Permafrost Areas (Pihlainen 1951)

A critical part of the “Active Method” is that the construction should not cause thermal disturbance to adjacent soil. The process of thawing in the adjacent foundations does not necessarily begin from a temperature raise, but the strength and characteristics of that frozen soil can still change dramatically. When the ground is disturbed, it usually has some sort of ripple effect to the surrounding foundations. In general, it is not a good idea to use both methods adjacent to each other. These should be taken into consideration in the planning phase. The development of surrounding thermal changes and soil characteristics can be monitored through instruments that collect data about temperature and movement. (Davison et al. 1981, 247-343.)

6 PERMAFROST IN THE PAST

6.1 “One of the Top 10 Construction Achievements of the 20th Century”

As described by J. David Rogers, the construction of the Alcan Highway in Alaska can be considered to be “one of the top 10 construction achievements of the 20th century”. The Alcan Highway (short for Alaskan-Canadian highway) was constructed during World War II as a military supply route for interior Alaska Military and Airfields in 1942. The highway was constructed under wartime conditions after the Japanese attacked the American Pacific Fleet at Pearl Harbor in 1941. Before that in the 1930’s, there had only been discussions about linking the “Lower 48” to Alaska. Due to the vulnerable nature of Alaska’s location to possible invasion and attacks, American military planners decided to develop a land link for the airfields and military forces residing in Alaska. (Hasselmann 2015.)

Already in the beginning of this amazing engineering feat, it was considered to be impossible to construct a road through the wilderness of the last frontier. Numerous difficulties and unprecedented engineering problems were battled and won during the construction, of which permafrost was one. Before this monumental achievement of constructing a road on land underlain with permafrost, all of the published literature on permafrost was then in Russian and knowledge on the subject was rare and highly sought after in North America. The US army loaned Stanford University Geology Professor Si Muller in 1943 to give his insights on frozen ground conditions in Alaska, as he wrote and spoke fluent Russian. (Hasselmann 2015.)

6.2 Background Details

The mission handed to the Army Corps of Engineer’s was to build a pioneer road that was suitable for military supply trucks as fast as possible. Amazingly, this was made possible in 8 months and 11 days (Hasselmann, 2015). After the pioneer road was completed, the task of upgrading the road to the status of a permanent highway was given to the U.S. Public Roads Administration. In November 20th 1942 the Alcan Highway was officially opened and it has been operating continuously ever since, known today as the Alaska Highway. (Hasselmann 2015.)

For the pioneer road, the Army Corps of Engineer's constructed 1,543 miles on treacherous ground after which 11,000 engineers were used to maintain and improve a total of 1,685 miles of highway. 41 American and 13 Canadian contractors helped in the improvement of the highway. (Hasselmann 2015.)

Table 1 below shows the final specifications of the highway for both the pioneer road constructed in 1942, and the Public Roads Administration's finished road in 1943.

Table 1. Final Specifications of the Alcan Highway

Highway Feature	Army Pioneer Road (1942)	Public Roads Administration Finished Road (1943)
Road Width	12 ft minimum	24 ft
Shoulders	3 ft minimum	6 ft minimum
Grades	10% maximum	7% maximum; 5% average
Curves	< 50 foot radius	717 foot radius
Surface	Compacted earth	2 feet crushed stone and gravel
Bridges	One-way H-15 loads	Two-way H-20 (20 tons/axle)

6.3 First Encounters with Permafrost

One of the essential problems that were countered with the construction of the Alcan Highway was soil underlain with permafrost. As known, permafrost is frozen soil which in degree is preserved by a cover of vegetation and soil. Commonly when constructing roads, the topsoil is removed and vegetation is stripped. This was a critical mistake when constructing on permafrost areas due to the disturbance of the temperature equilibrium. When the temperature equilibrium of the soil was disturbed, the frozen subsoil would begin to melt and create nearly impassable muddy terrain (see Figure 18). Thawing of the soil then produced foundation problems (loss of shear strength) such as muskegs.

Figure 18. Effects of Thawing After Vegetation and Topsoil Removed (Hasselmann 2015)

Removal of topsoil was necessary in most parts but it was quickly learned how to treat the problem of losing shear strength. The topsoil layer was often frost susceptible with fine sand and silt, having the property of heavy heaving. The solution then came down to choosing whether to construct the road with the passive or active method. As a reminder, with the passive method the construction is done by attempting to preserve the permafrost and not disturb the temperature equilibrium of the soil, and the active method of construction focuses on removing the problem by filling the base with new material. The pioneers addressed the situation by using gravel fills (as seen in Figure 19) that were favorable due to its non-frost susceptible nature as fill material (Hasselmann, 2015). Losing excess quantities of frost susceptible material from the fill was sought after, as it increased the heave rate when the fill froze. Some areas during construction were layered with corduroy brush mats that preserved and solidified the foundation as much as it could (Figures 19 and 20). The corduroy mat worked similarly to modern insulation.

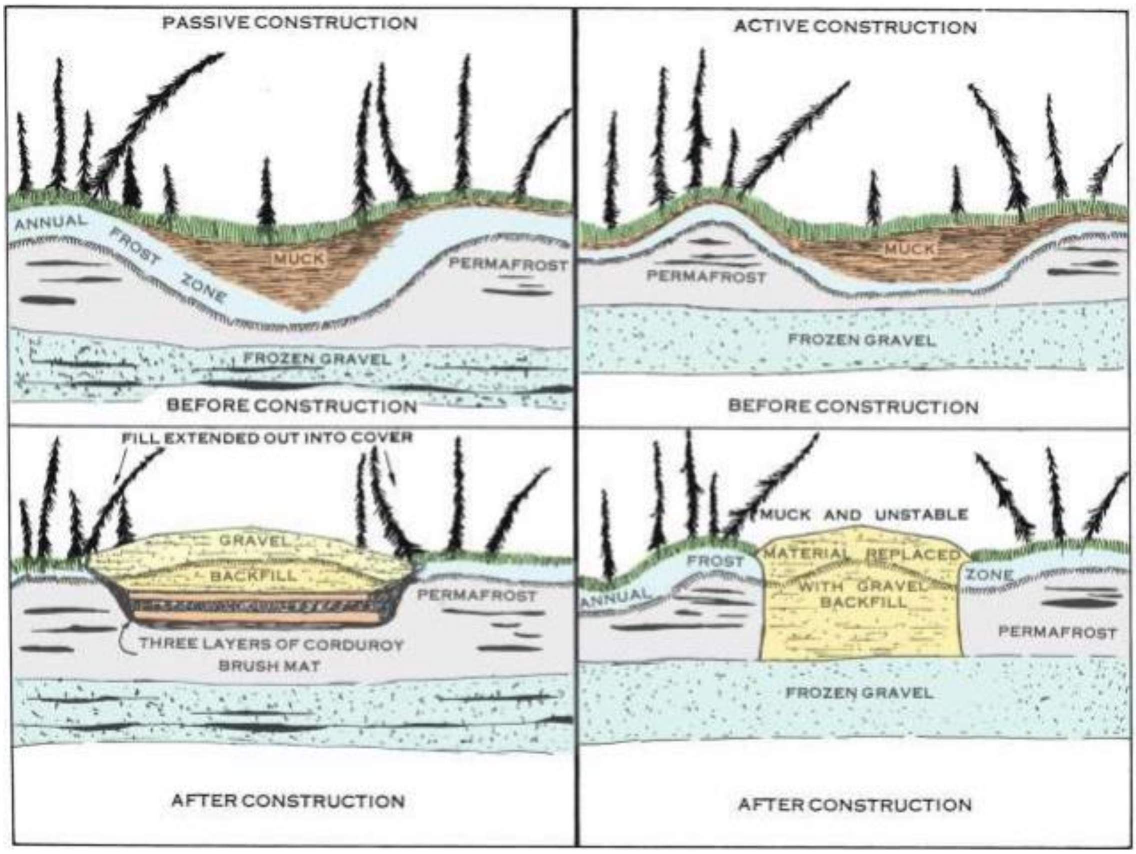


Figure 19. Passive and Active Construction on the Alcan Highway (Hasselmann 2015)

Figure 20. Parts of Alcan Highway with Corduroy Brush Mats (Hasselmann 2015)

Deterioration of the road fills (differential settlement and slumping) due to severe thaw-susceptibility was another big concern during this engineering feat. Most of the problems encountered required imagination and creativity to be solved through trial and error, but sometimes previously conducted research and information can be crucial. With extremely severe condition of thaw-susceptibility, the construction of a berm is recommended (Shur 2015c). Muller discovered from Russian technical literature that they employed shoulder berms to check for slumping and deterioration, and berms were then constructed. Berms help to maintain the temperature equilibrium favorable to permafrost (Shur 2015c).

7 MODERN ROADWAY ENGINEERING

7.1 Roadway Distress

Typically, roadway distress in warm permafrost areas is caused by side slopes after long-term thaw related settlements (Esch 1983, 7-12). This occurs due to the fact that the soils underlying the snow-covered slopes do not fully freeze from one winter to another. The snow cover on the side slopes acts as an insulation and can hinder the refreezing of the slopes. This, in turn, depends on the depth of the snow cover and whether it exceeds the critical depth of snow. (Shur 2015, 1-73.) The concept of critical depth of snow was first introduced by Kudriavtsev (1959). If the depth of snow is equal to the critical depth, the temperature of the soil at the bottom of the active layer is equal to 0°C. Therefore in this scenario where the long-term thaw related settlement causes roadway distress from the side slopes, the snow depth has exceeded the critical depth causing warmer temperature regime and the permafrost table retreats. As mentioned earlier, this can then cause progressive settlement on the edges of the road and longitudinal cracking of the surface (see Figure 21). (Shur 2015, 1-73.)

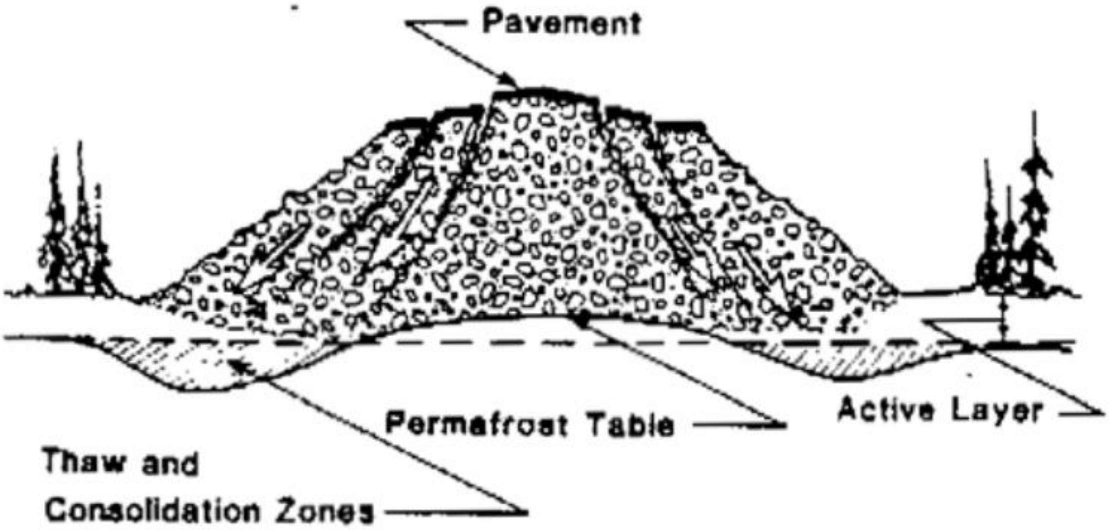


Figure 21. Thawing Beneath Side Slopes Causes Distress (Esch 1983, 7)

7.2 Embankment Research Project

As side slopes and especially the embankment slope design of a road seemed to be a great factor in controlling thaw beneath side slopes, a research project was initiated in 1973 in Fairbanks, Alaska. The project was used to study and determine the benefits of different designs, but also evaluate alternative insulated roadway designs for road sections where vegetation had to be removed. The research project group used ten different combinations of insulated layers, toe berms, and air ducting systems on brand new highway sections just 40 km west of Fairbanks. The installations were done during 1973 and 1974. Monitoring of the experimental sections began in 1974 after the installations were completed. (Esch 1983, 7-12.)

The sites (Alder Creek and Bonanza Creek) were located in areas where the roadway segments ran over undisturbed terrain underlain by ice-rich silt permafrost soils. The Alder Creek site had black spruce and sphagnum moss vegetation cover with organic colluvial silts as soil. Permafrost was found generally beneath a shallow 0.6m thick active layer. Moisture content was high (ice-rich permafrost) ranging from 30% to 90%. Massive ice was found in nearly all borings between depths of 4.5 and 14m. At Bonanza Creek the permafrost had a 0.3-0.6m thick peat active layer covered with a sphagnum moss and scattered black spruce. Frozen organic silts were also found beneath the peat layer. The organic silts had a frozen water content ranging from 30 to 380% (averaging around 100% by weight). Opposite to Alder Creek, no massive ice was encountered. (Esch 1983, 7-12.)

Figure 22 shows the experiment and what was installed in Bonanza Creek.

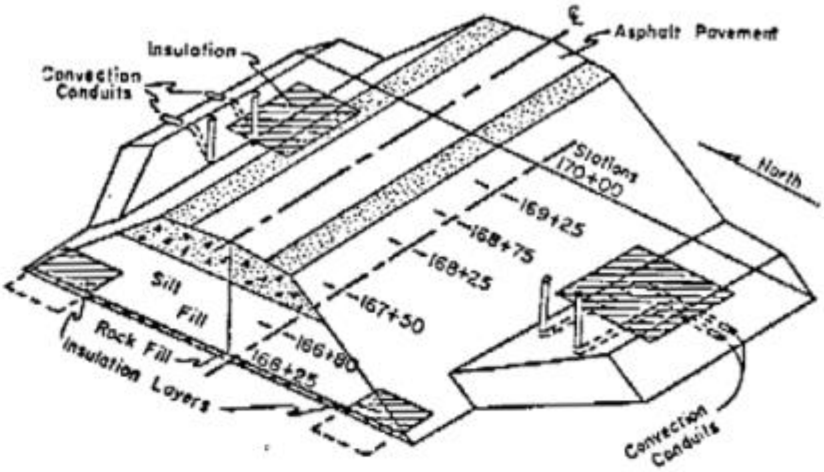


Figure 22. Bonanza Creek Overlay of Experimental Installations (Esch 1983, 10)

7.3 Air Ducts

The study revealed that the air convection cooling ducts used turned out to be of significant benefit in decelerating the thaw of the foundation soils. When paired with insulation layers, the air ducts worked well in reducing the summertime heat gains. Nevertheless, the study also indicated that the ducts used could have been more beneficial with larger diameter ducts. During the monitoring, it was also noted that the ducts could have been located closer to the center of the embankment to affect the shoulder and surface movements more favorably. (Esch 1983, 7-12.)

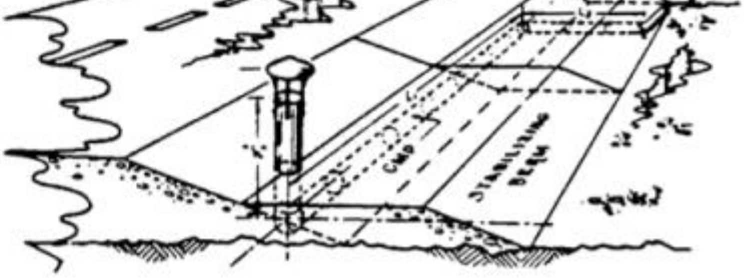


Figure 23. Air Convection Cooling Duct Installed on the Field (Zarling, Connor & Goering 1983, 14)

7.4 Embankment Toe Berms and Insulation Layers

The embankment toe berms constructed for the study were made of silt or waste materials. These berms ended up showing only few or very minor benefits on thaw beneath the side slopes. Minor benefit of having these berms is being able to decelerate the progressive thaw settlement by 1-3 years. Out of the several design choices, a 6m berm width was slightly more preferable to a 3m when looking at a short-term basis. The study concluded that neither berm type prevented long-term thaw progression. Additionally to showing few benefits in retarding thawing, toe berms showed some effectiveness in reducing lateral shear-type movements and settlement. These benefits were due to the supporting and counterbalancing effects which could be found in the lower and mid-slope areas. (Esch 1983, 7-12.)

In contrast but not unexpectedly, insulated toe berms showed major reduction in thawing. Using 51mm of insulation compared to the above mentioned uninsulated berms provided delayed thaw progression into the underlying permafrost by about 4 years. Similar to the uninsulated toe berms, the insulated toe berms could not trump the long-term thawing trends beneath the slopes and berms. Berms are still critical since using insulation layers at a height of 1m above the toes of a normal embankment without any kind of berms, showed no positive results in decelerating thawing or other related problems. (Esch 1983, 7-12.)

7.5 Summary of the Bonanza Creek Study

In the study of alternative roadway insulation designs, a continuous record of roadway cuts, embankment movements and thermal changes were kept between the years 1974 and 1982 near Fairbanks, Alaska. Ten instrumented roadway sections were used with various installations of air ducts, insulations and embankment designs. In all cases, the permafrost conditions were preserved under the roadway and shoulder areas. Cut section with insulation installed at the depth of 3.2m showed disproportionate thawing compared to a similar section with insulation at a 1.2m depth which had nearly inconsequential thaw settlement.

All areas still developed taliks and residual thaw zones at the side slopes. This progressive thawing that increased annually resulted in growing deformation and cracking of slopes and roadway shoulders. (Esch 1983, 7-12.)

Nevertheless, the study at Bonanza Creek reveals that the benefit of a combination of insulation layers, air cooling ducts, and embankment toe berms were apparent. The use of any single strategy shows minor benefits, but a combination proves to be most successful. Even though beneficial, no combination in this study showed satisfactory cure to prevent long-term thaw settlements. What this means is that eventually the 7m high road embankment will face roadway surface distortions. Even with warm permafrost conditions (-0.6°C), a successful combination of larger air cooling ducts (as mentioned previously), embankment design and insulation design may be adequate to provide a thermally stable embankment to offset annual heat gains. (Esch 1983, 7-12.)

8 PERMAFROST IN FINLAND

Permafrost in Finland is not perhaps the greatest of issues but is nevertheless a matter to be closely examined. As described earlier, Finland contains scattered land areas underlain with permafrost that can be described as sporadic permafrost. Sporadic discontinuous permafrost describes individual areas of permafrost that are surrounded by unfrozen ground. In Finland’s case, all of the permafrost sites are located above the Arctic Circle, close to the northern borders of Finland. Most of the sporadic permafrost sites are within palsa mires in northern Lapland. Most of the palsa mires are concentrated around Utsjoki and the Enontekiö municipality between Norway and Sweden (Suomen Ympäristökeskus 2010). Permafrost in Finland can be described as “warm” permafrost and sensitive to climate change (Gurney 2005, 1-32). Finland also has the pleasure of introducing the word “palsa” into the permafrost engineering vocabulary.

Palsas might be the more well-known example of permafrost found in Finland, but Finland also has permafrost in bedrock and in caves. Permafrost in bedrock can be easily described as frozen bedrock where the temperature remains continuously below zero degrees centigrade (Seppälä 1997, 87-96). Such previously unknown bedrock permafrost was found in summit areas of fells with frozen ground of 10-50 m in thickness. Scientists then extrapolated that there might be even permafrost with thickness of more than 100 m at the highest mountains, like Mt. Saana at Kilpisjärvi (Seppälä 1997, 87-96). Previously, it was thought that permafrost in Finland would only cover the mires found in northern Finland, but it has been proposed that the distribution goes far beyond the palsa regions into the fells above the tree line. In the 1990s, cave ice was found in northern Finland. Cave ice was then added into the permafrost distribution of Finland. Cave ice is not as common as the two previously mentioned permafrost types found in Finland.

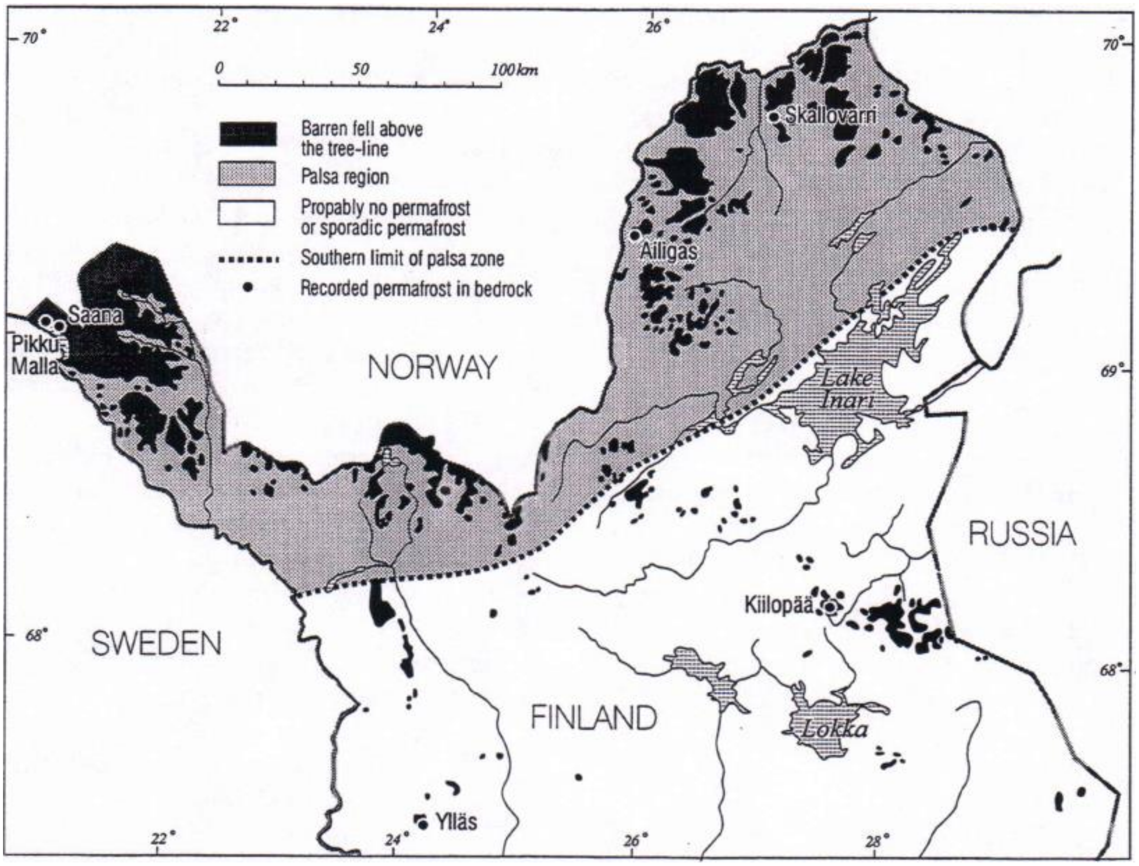


Figure 24. Permafrost Distribution in Northern Finland (Seppälä 1997, 89)

The palsas in Finnish Lapland tend to grow up to 7 m above the surrounding mire. Interestingly, the palsas in Finland usually reach the same depth into the ground as they grow upwards from the surrounding surface (Seppälä 1997, 87-96). As an example, if the palsa is 5 m in height, the total thickness would be at least 8-10 m. A common indicator of permafrost and of palsa mires is the absence of larger plants. In Finnish Lapland, large trees do not grow on permafrost locations. (Seppälä 1997, 87-96.) The most common vegetation type found in permafrost areas in Finland tends to be low or medium heath vegetation. Such vegetation includes different kinds of moss (sphagnum moss and reindeer moss), grass (cotton grass), and berries (crowberry and cloudberry). (Gurney 2005, 1-32.) Vegetation above the palsas usually survive with a thin snow cover which is common for palsa mounds. If the snow cover is deep, the likelihood of palsa formation is low and the vegetation is, in turn, different as well. Snow cover acts as a strong insulator and is a critical factor in permafrost formation. Interestingly in palsa mires, once permafrost begins to form, the previous vegetation usually dies and new species take over. (Seppälä 1997, 87-96.)

Soil types found in northern Finland are gravel, sand, till, silt and peat. All of these soil types freeze; but out of these, mostly silt, peat and silty tills are highly susceptible to frost actions. From these three frost active soils, permafrost can be found in silt and silty till. The surrounding mires offer the water supply, which together with cold winter temperatures then enable the frost features to form in Northern Finland as seen in Figure 25. (Seppälä 1997, 87-96.)

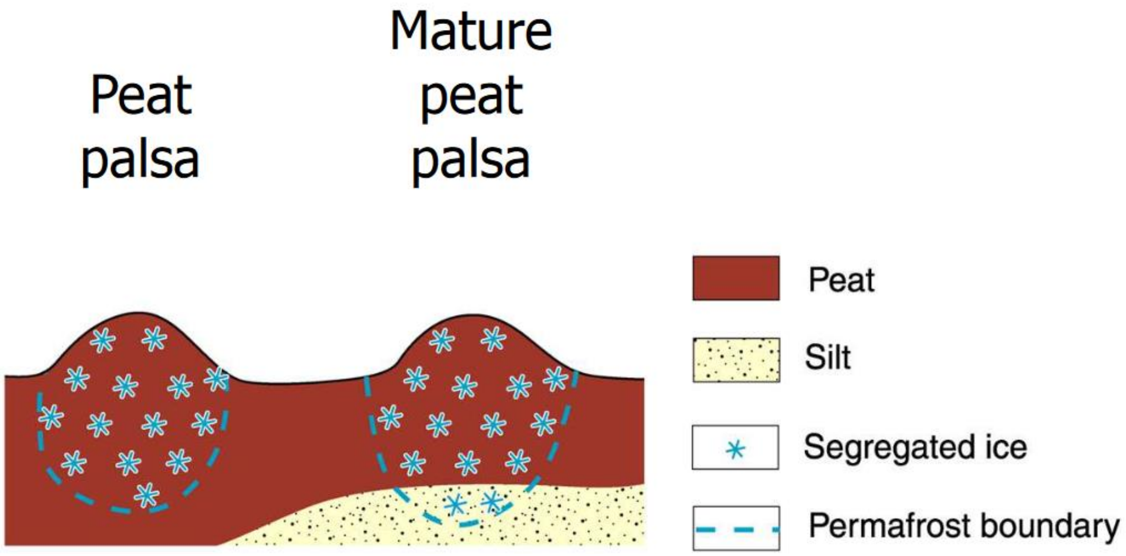


Figure 25. Palsa Types and Example of Soil Characteristics in Northern Finland (Gurney 2005, 17)

Palsa mires in Finland are constantly evaluated to investigate the effects of climate change, snow cover, wind and many other factors on palsas and permafrost ground in general. Northern Finland luckily possesses cold enough temperatures, strong winds, low vegetation and varying snow cover that allow ideal research conditions for scientists. Research on how climate change affects a palsa gives scientists a good idea on how the temperature flux changes the bog habitat and surrounding palsas. As the annual mean temperatures continue to rise, the palsas will collapse and contribute to watering bogs even more. These radical changes of habitat can have an impact on local flora and fauna.

Additionally, it may even be so that no new ice will form within the core hearts of palsas. This would mean that the currently found palsa distribution may be just a fraction or a small remnant of the previous distribution. Another worrying thought is that the permafrost decay in marsh areas contribute to climate change through methane release. (Gurney 2005, 1-32.) At the moment the balance of environmental conditions seem to be fairly good, so the old palsas are collapsing at approximately the same rate as new ice cores are forming (Seppälä 1997, 87-96). Above mentioned bedrock permafrost on the other hand require extremely drastic change to be affected by the climate change. For deep bedrock permafrost to begin to thaw also requires much more time to have fatal effects.

Permafrost engineering examples can be also found in northern Lapland. There are a few locations (at Kilpisjärvi, northern Finland) where a road has been built on top of small permafrost patches. These patches have begun warping the road and causing a demand for repair. If the road is to be kept on the same position, a well thought out plan must be made on how to address the issue. As described earlier, engineers have to decide carefully on what kind of foundation design they will use. Generally speaking, permafrost can found at the mires and fell summit areas of northern Finland, and apart from the very few examples of roads, there has been no construction on perennially frozen ground (Keskisuomalainen 2016).

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