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Understanding and Developing Estimates Based on Practical Foundation Methods for Alaska's Discontinuous Permafrost Region

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UNDERSTANDING AND DEVELOPING ESTIMATES BASED ON PRACTICAL FOUNDATION METHODS FOR ALASKA'S DISCONTINUOUS PERMAFROST REGION

THESIS

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DEPARTMENT OF THE AIR FORCE
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UNDERSTANDING AND DEVELOPING ESTIMATES BASED ON PRACTICAL FOUNDATION METHODS FOR ALASKA'S DISCONTINUOUS PERMAFROST REGION

THESIS

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Abstract

This research uses a quantitative analysis to develop a family of curves and a calculator for potential foundation thresholds in the discontinuous permafrost region of Alaska. The United States Pacific Command (PACAF) is bolstering the region by advocating for the F-35, KC-46, and the newly proposed long-range bomber to be stationed in Alaska. These next generation aircrafts and warfighters will need new facilities and beddown plans to efficiently and effectively carry out their mission. The biggest obstacle in the region is permafrost; this unique polar phenomenon is found throughout the northern half of Alaska. Fairbanks in particular has multiple military bases that could benefit from knowing which foundation type would excel in the region. With the help of seven experts in construction, excavation, and geotechnical engineering fields, the researcher discussed methods of constructing a fictitious foundation located at Eielson AFB. The average regional cost per cubic yard of soil is $4.13; however, the average cost to excavate permafrost catapults to $11.50. With different types of proven foundations used in Alaska, all experts agreed that helical piles and thermosyphons are for extreme scenarios and would not be cost-effective in the discontinuous permafrost region. Concrete piles and excavation being the two true contenders for the area, the researcher discovered that excavating is superior to concrete piles until the volume of permafrost exceeds 94% of the construction site. Even though Fairbanks has one of the cheapest concrete batch plants in Alaska, excavating and hauling fill materials miles away is ultimately cheaper for the military.

Acknowledgments

I would not have made it this far if it was not for the friends and family that surrounded me during this journey.

Paul P. Dennison

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UNDERSTANDING AND DEVELOPING FOUNDATION METHODS BASED ON ALASKA'S DISCONTINUOUS PERMAFROST REGION BY LIMITING FACTORS

I. Introduction

The United States Pacific Command (PACAF) overlooks 36 nations and 52% of the Earth's surface, all while deterring enemies on America's western front with three Air Force and six other military installations ("Alaska Military Bases," 2017; United States Pacific Command, n.d.). PACAF is constantly posturing to expand their geographic range not by increasing the requirement of new operating bases in the region, but by continued enhancement of current sustainable and operationally resilient bases. The detection of permafrost land within the respective areas of established bases presents an increased vulnerability to their mission critical assets. They are trying to address these concerns by ensuring the survivability of their existing assets (United States Pacific Command, n.d.). With PACAF's recently gained warfighter platforms, including the F-35, KC-46, and the newly proposed long-range strike bombers, an extensive beddown is required on multiple installations in the PACAF region (United States Pacific Command, n.d.). A beddown is a development plan of where to strategically put assets and all supporting facilities required to maintain the new mission.

Alaskan bases, in particular, are affected by permafrost, a northern region phenomenon. Climate change and disturbing the natural ecosystem have the potential of affecting the permafrost and reshaping strategic military installations (United States

Pacific Command, n.d.). One large concern is construction on permafrost; more specifically, the loss of bearing capacity due to thawing. A mathematical model indicated by the mid-21st century that up 20-25% of the permafrost regions will be reduced by climate change induced thawing (Schuur et al., 2015). Permafrost thawing is a serious concern when constructing new facilities. Differential settlement and loss of bearing capacity are affected by both climate change and anthropogenic effects in the discontinuous permafrost region (Estus, 2014; McFadden, 2001).

Construction in the northern tier region is a delicate process; the irregular deposits of permafrost are a unique factor for construction that determines the integrity of the building's superstructure in the later years of its service life. The northern tier region is dominated by a longer winter season (National Weather Service Alaska, n.d.). A major concern for the Department of Defense (DoD) and PACAF is the allocating and budgeting of funds to produce functional buildings in the northern tier region. PACAF has stated that the current fiscal environment and competing national priorities are not conducive to fulfilling regional operations and traditional security roles (United States Pacific Command, n.d.). These fiscal constraints limit the design capabilities for military installations that do not have enough time or funds to properly investigate potential sites for all unknown conditions – to include permafrost.

This research focused on building foundations through the lens of permafrost and construction cost. Foundations most commonly used in Alaska will be the engineering focal point of this research. This will allow the DoD and PACAF to increase mission effectiveness by requiring appropriate funding needed to beddown a mission and focus more on the region's strategic operations. Optimizing the construction budget has the potential of reallocating funds to other operations.

1.1 Background

Permafrost is a term coined by S.M. Muller in 1943 to shorten the term “Permanently Frozen Ground” (Yershov, 1998). It describes permanently frozen soil that has remained frozen for a minimum of two consecutive years (Carlson, 2011; Clarke, 2007; Crawford & Johnston, 1971; Ferrians, Kachadoorian, & Greene, 1969; McFadden, 2001; Muller, 2008); however, most of the permafrost regions have been around for tens of thousands of years. The further north one goes in the northern hemisphere, the more extensive permafrost becomes (Carlson, 2011; Clarke, 2007; Muller, 2008). An estimated 20-25% of the northern hemisphere's terrestrial surface is covered by permafrost (Anisimov & Reneva, 2006; Strauss et al., 2017). Figure **1** displays the range of all permafrost in the northern hemisphere. This covers a large portion of strategically placed bases in Alaska where permafrost can be found – both in continuous and discontinuous forms. Permafrost can only exist if the flow of heat into the soil is less than the heat leaving the soil (Clarke, 2007). In other words, even during maximum heat input from the sun and other factors of heat, permafrost must remain below freezing. Continuous permafrost is when all of the ground's subsurface is made up of frozen soil. Discontinuous permafrost is only made up of patches of frozen chunks of soil. It was observed that warming, thawing, and degradation of permafrost has accelerated over the decades, most likely as a result of greenhouse effect and climate change (Schuur et al., 2015; Whiteman, Hope, & Wadhams, 2013).

Figure 1. Permafrost locations in the northern hemisphere (NSIDC, n.d.)

The change in permafrost impacts more than just the soil. It also implicates new construction requirements (Andersland & Ladanyi, 1994; Muller, 2008; Yershov, 1998). The concerns include, but are not limited to, differential settlement, exterior damage, and economic impacts (Bell & Ashwood, 2016; Clarke, 2007). Soil bearing capacity is the basis for foundation design and plays a large role in differential settlement. Bearing capacity is the average value of pressure that a soil can withstand before producing shear failure, the load of the weight sitting on top of it ("Bearing Capacity Technical Guidance," 2012). An example through this definition is that the weight of a building must be less than the soil and permafrost's allowable pressure.

1.1.2 Difference Between Permafrost and Seasonal Frost

Permafrost can be found under the seasonal frost line (Carlson, 2011; Jorgenson, Yoshikawa, Kanevskiy, & Shur, 2008; Muller, 2008; Strauss et al., 2017). The frost line is how deep the ground freezes during one winter cycle at a given location, usually dictated by the state or county level. Seasonal frost forms in the winter and thaws during the summer season. When seasonal frost forms over permafrost, it is then considered to be an active layer in which it insulates the permafrost and acts as a barrier from heat sources (Carlson, 2011; Muller, 2008).

1.1.3 Soil Composition and Content

Soil composition is made up of different percentages of sands, silts, gravel, organic matter, and water content (Smith & Mullins, 2000). Permafrost has a significant correlation with soil temperature and moisture; thus, broken into two categories: "thaw-stable" and "thaw-unstable" (Andersland & Ladanyi, 1994; Bell & Ashwood, 2016; Finger et al., 2016; Kurylyk et al., 2016). These terms replaced the original ones of "nondetrimental" and "detrimental" permafrost to better accurately describe the disappearance of permafrost (Brewer, 1958; Ferrians, Kachadoorian, Greene, Hickel, &

Pecora, 1969). "Thaw-stable" permafrost is better to build on without taking on intricate measures to counteract the permafrost, since the soil is in contact with one another, thereby creating a stable base for a foundation and road (Bell & Ashwood, 2016; Hong, Perkins, & Trainor, 2014; Smith & Mullins, 2000). "Thaw-unstable" is just the opposite; the grains of soil are separated by ice, so when the thawing process is introduced, the soil will settle to a greater depth than "thaw-stable" permafrost (Bell & Ashwood, 2016; Hong et al., 2014; Smith & Mullins, 2000).

The measurement of water content (moisture) is fundamental to many soil investigations in ecology, hydrology, and civil engineering (Smith & Mullins, 2000). The cause of most damage to the foundation or superstructure of a building is the soil, and in Alaska's unique case, permafrost. Soils found in Alaska can create a potential of unequal settlement which causes distress to the building if not properly investigated (Bell & Ashwood, 2016; Clarke, 2007; Wei, Guodong, & Qingbai, 2009; Yershov, 1998). Settlement of a facility occurs over 1-10 years depending on the weight of the building (Alfaro, Asce, Ciro, Thiessen, & Ng, n.d.; Bell & Ashwood, 2016). Another settlement factor is the permafrost's thaw rate that shrinks the soil volume underneath the foundation (Alfaro et al., n.d.).

The path to achieving 100% water saturation varies for each soil type. Course-grained soils, such as gravel, have the ability to absorb and store 5% of its dry weight in water (Brady & Weil, 1999; Kramarenko, Nikitenkov, Matveenko, Molokov, & Vasilenko, 2016). Fine-grained soils can hold up to 17%, while soils with high levels of organic matter can retain up to 30% (Brady & Weil, 1999; Kramarenko et al., 2016). The dangers of fine-grain soils and permafrost are recognized during the thawing process when the soil becomes “soupy,” thus creating additional risk for the foundations to settle unevenly (McFadden, 2001).

The thermal balance of permafrost is unique. As part of the main definition, it stays below freezing but maintains a strict equilibrium with the surrounding environment (Whiteman et al., 2013). If left unchecked, buildings with a large heat output may suffer settlement issues (Bell & Ashwood, 2016; Muller, 2008).

1.1.5 Location of Permafrost

Currently, there are total of nine military installations in Alaska (“Alaska Military Bases,” 2017). Figure 3 shows major bases affected by the presence of permafrost – excluding coast guard stations. A majority of these installations reside in the University of Alaska's 2008 map, Figure 2, of potential permafrost regions in Alaska (Jorgenson et al., 2008).

Figure 3. Locations of Military Bases in Alaska (Lange, 2017)

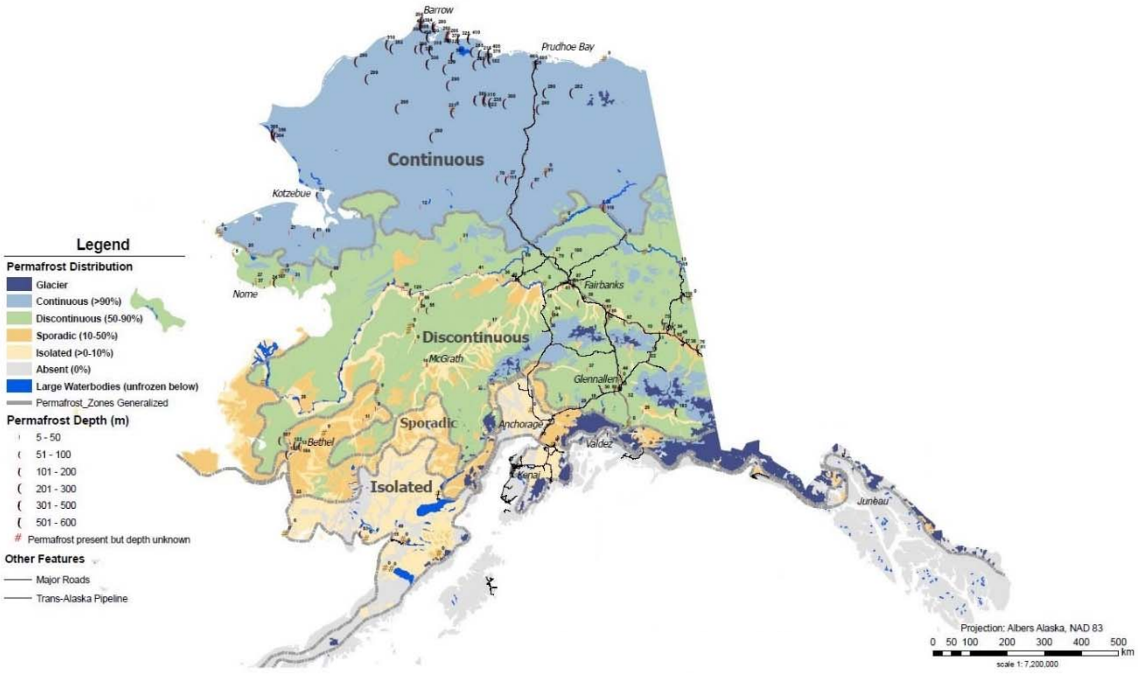


Figure 2. Permafrost Regions of Alaska (Jorgenson et al., 2008)

Permafrost can be located above the 60 degree latitude, with the rare occasions found beneath lakes, rivers, and wetland type areas due to the increased mean temperature (Clarke, 2007; Günther, Overduin, Sandakov, Grosse, & Grigoriev, 2013; Jones et al., 2011; Kanevskiy, Shur, Fortier, Jorgenson, & Stephani, 2011). As seen in Figure **1** and Figure 2, the further south you get from Barrow, Alaska, the less abundant continuous permafrost becomes and the discontinuous permafrost regions take shape, leading to degradation of soil and unstable ground conditions (Alfaro et al., n.d.; Carlson, 2011; Clarke, 2007; Jorgenson et al., 2008). Even though continuous permafrost is by definition continuous, natural breaks in terrain may change the formation of permafrost (Finger et al., 2016; Muller, 2008). Near the northern coast of Alaska, permafrost extends for acres at a depth of several hundred meters below the active layer (Carlson, 2011; Hinkel & Nelson, 2003). Permafrost near Fairbanks, Alaska, is intermittent, but it still has the potential of housing large chunks that can disrupt the expansion of man-made structures (Carlson, 2011; Hinkel & Nelson, 2003). The three military installations near Fairbanks, Alaska, are within the discontinuous permafrost region. The DoD will benefit from historical construction trends in Alaska to examine the cost of constructing foundations for emerging beddown programs. The extent of these zones has the potential of spanning a couple of feet to a few acres in size. The true locations of permafrost are unknown due to climate change and natural contours of the landscape; this creates a high-risk endeavor for engineers trying to design and erect superstructures in the area.

1.2 Problem Statement

A gap in knowledge exists regarding the most cost-effective foundation transition points for the northern tier's discontinuous permafrost region. The amount of permafrost at any given site could indicate a preferred method in constructing a building's foundation.

1.3 Purpose

The United States Army Corps of Engineers (USACE) Cold Regions Research and Engineering Laboratory (CRREL) attempted to collaborate with other engineers to create of a permafrost construction flowchart – back in late 1970s. Special Report 80-34 tried to create a comprehensive design guide for foundations in areas with deep seasonal frost and permafrost (Linell & Lobacz, 1980). The charts included numerous variables such as soil type, water content, amount of permafrost, region, and estimated freeze-thaw cycles (Linell & Lobacz, 1980). Published in 1980, it reduced the amount of work required take when designing or constructing a foundation. This research will limit the number of variables to amount of permafrost, depth, and occupational use of the facility. With those three driving factors, the research resulted in a cost-effective plan based on limited factors rather than the fluctuating details present at a construction site.

This study used quantitative data and current cost estimates from local experts in the region to produce foundation type thresholds. The study created a family of curves and a calculator regarding the cost of different foundation methods and the amount permafrost. A comparison between all the foundation types determined which foundation is the most effective when constructing facilities in an area with permafrost.

1.4 Significance

With the increased presence of military assets in PACAF, the number of beddown sites to accompany the new mission assets will also increase. This uptick of construction may cause long-term damage to facilities on one of the many installations found in Alaska, thus causing emergent requirements to repair, maintain, or even replace critical infrastructure in the near future. Climate change is just one factor of thawing permafrost. Building on top of unknown patches creates a larger and more immediate concern for the permafrost. The research focused on preventing the latter from happening by presenting the better overall fit when designing permanent facilities on military installations located in the northern tier region. To establish a correlation, the research will utilize current construction techniques used by experts in the region to determine related themes that link construction cost, facility use, and presence of permafrost to accurately predict construction methods.

1.5 Primary Research Questions

Using the occupation use, amount of permafrost, and depth of construction as the three main factors, the research answered these three questions:

- Which foundation type is the most cost-effective in the discontinuous permafrost region?
- At what point should engineers consider transitioning to a different foundation type?
- What foundation types are typically used in the discontinuous permafrost region?

1.6 Summary

To ignore permafrost while constructing buildings in the northern tier region will result in inevitable catastrophe if meticulous site investigations do not occur (McFadden, 2001). When building the Qinghai-Tibet Highway in China, 85% of the problems resulted in lack of engineering when dealing with the intermittent presence of permafrost and the accompanying settlement issues (Zhizhong, Wei, & Dongqing, 2005a). Over the centuries, the northern hemisphere's discontinuous permafrost regions were once continuous before the introduction external factors such as construction, climate change, and the redirecting of bodies of water (Carlson, 2011; Kanevskiy et al., 2011; Nash, 2009). Permafrost in the discontinuous region is in a fragile state, and most patches of permafrost cannot withstand 1-2 degree Celsius increase in mean annual temperature (Clarke, 2007; Finger et al., 2016; Muller, 2008). The iterative freeze-thaw action will lead to geoengineering challenges through thaw settlement, frost heaving, icing, and gelifluction which jeopardize the stability of buildings (Zhizhong, Wei, & Dongqing, 2005b).

There is not enough conclusive data that the majority of permafrost will disappear, but the southern regions will face some rate of thaw based on current trends (Anisimov & Reneva, 2006; Strauss et al., 2017). There is concern over existing buildings and their foundations; they will encounter disaster because of the thawing of permafrost that the foundations depend on staying frozen (McFadden, 2001; Nash, 2009; Nixon, 1978; Shankle, 1985). Failure due to permafrost will not lead to immediate danger or sudden collapse, but left unattended, the building will become unsuitable for use due to compromised safety (Clarke, 2007; McFadden, 2001; Muller, 2008). Construction in Alaska requires specific knowledge about permafrost and specialized building techniques in the region or uneven settlement issues will form and disastrous consequences for the building will eventually happen (Clarke, 2007; Crawford & Johnston, 1971).

II. Literature Review

The first portion of the chapter examines the issues of Alaskan construction. The majority of the chapter focuses the advantageous and disadvantageous for each primary foundation method used in the region. Closing out this chapter the researcher examined the labor and economic market surrounding Fairbanks, Alaska.

2.1 Engineering Problems Surrounding Discontinuous Permafrost

The northern tier region is plagued with sporadic permafrost along the center portion of Alaska. Engineers are now focusing more on site surveys and geological exploration to obtain detailed information of existing conditions than ever before (Shankle, 1985). This process is extensive and does not always account for all discontinuous permafrost locations in the region. A primary design challenge in the discontinuous permafrost belt is how to effectively construct structures on top or near the known pockets of permafrost with minimal impact to finished structure. The interaction between the new building's expected thermal discharges and the stability of permafrost is filled with uncertainty.

Discontinuous permafrost requires special consideration to construct buildings on the Alaskan frontier than temperate climate regions (Nash, 2009). In Alaska, the greatest near-term risk for thaw settlement for buildings, roads, and other infrastructure is found in the discontinuous permafrost region (Hong et al., 2014; Melvin et al., 2017). Since permafrost is a widespread naturally occurring phenomenon in Alaska, consulting with experienced engineers and contractors will provide insight on how to effectively construct in the northern region (Nash, 2009; Shiklomanov, Streletskiy, Grebenets, & Suter, 2017). Permafrost covers roughly 85 percent of the state of Alaska and ranges in thickness between a couple of meters in the south to 400 meters (1,300 feet) in the north (Ferrians et al., 1969). The lack of permafrost knowledge has resulted in increased maintenance costs or abandonment of the assets. These errors cannot be overlooked when designing facilities to house and maintain the Air Force's newest additions to the warfighter capabilities.

An increased thermal discharge into the permafrost would result in differential settlement to a building, thereby causing more issues for the users (Ferrians et al., 1969). Construction has a thermal impact on the surrounding environment's thawing process (UFC3-110-03, 2004). Changing the thermal properties has a negative impact on establishing cost-saving efforts in the arctic environment. Engineers and contractors must preserve the natural environment so that the permafrost has a lesser chance to thaw and disrupt the building (Ferrians et al., 1969; Widianto, Heilenman, Owen, & Fente, 2015). A common occurrence in Alaska is differential settlement; Brewer (1958) discussed that some heated buildings at Barrow have settled as much as 50 cm (20 in) in a span of three to four years. The initial cost of properly designing a building and protecting the permafrost far outweighs the expensive life-cycle repairs and increased maintenance cost accumulated by the owner of the building (Shiklomanov et al., 2017; Yu et al., 2016). Another source of cost saving application includes protecting the fragile thermal equilibrium by leaving as much surface vegetation as possible to incorporate the natural insulating effect (Crate et al., 2017). With PACAF's need to maintain their mission, future construction projects will need guidance on the most time and cost-effective way of dealing with discontinuous permafrost based on past performances of Department of Defense (DoD) buildings in Alaska.

2.2 Design and Construction Approaches to Discontinuous Permafrost

Climate change alone has increased the cost to perform services in the permafrost regions by an estimated annual expense of $50 million (in 2015 dollars) (Cole, Colonell, & Esch, 1999; Melvin et al., 2017). By 2080, it was estimated that $7.3 to $14.5 billion dollars will be used to perform extensive repairs and maintenance due to thawing, flooding, and coastal erosion in Alaska (Larsen et al., 2008; Melvin et al., 2017).

The three fundamental approaches to designing and constructing a building within the discontinuous permafrost region are:

1) Maintaining the thermal balance of the surrounding permafrost with respect to the mean annual temperature (Yershov, 1998).
2) Removing all permafrost from the area to ensure preservation of the structure (Yershov, 1998).
3) Defining the buildings life-cycle determines the extent of design (Shankle, 1985).

The first and second point are made by Yershov (1998) and his belief in minimalist impact design and construction. The third fundamental approach comes from a 1985 report titled “Design of Foundations in Permafrost.” The third approach, designing facilities to its potential life-cycle, is a decision made by the user before the implementation of the other two major techniques; therefore, removed from the discussion of this thesis. Both approaches have been tested throughout the past century and are still viable in today's permafrost regions (Krzewinski, Ge, & Ross, 2013; Shiklomanov et al., 2017; Widianto et al., 2015). Determining the environmental conditions will dictate the engineer's design response (UFC3-110-03, 2004). Another piece of the construction puzzle is longevity. The type of structure determines the method of design (Shankle, 1985). A permanent structure, lasting 25-30 years, will be designed differently with stricter tolerances than a temporary structure lasting up to five years (Shankle, 1985).

2.3 Regional Construction Techniques

The first method ensures structural stability by removing all soil related threats, including fine-grained soils, and replacing them with larger granular soil that is less susceptible to Alaska's freeze-thaw cycle (McFadden, 2001; Widianto et al., 2015; Yershov, 1998). This increases the earthwork and additional fill material costs of a project, but it protects the building from large amounts of differential settlement and frost heave in the future.

The second method is to keep the ground frozen through natural or mechanical procedures. The removal of heat transfer is a basic concept that Tsytovich (1928) developed. This can be achieved by conserving the surrounding permafrost's existing temperature (UFC3-110-03, 2004). The natural procedure is a way of maintaining the subsurface temperature without artificial enhancements to the building (Ferrians et al., 1969; Krzewinski et al., 2013; McFadden, 2001; Shiklomanov et al., 2017; Widianto et al., 2015; Yershov, 1998). The most simplistic method is to construct a crawlspace with a height of 0.5 to 2.0 meters so the heat dissipates before reaching the ground (Yershov, 1998). However, the method is not without an added caveat. Enclosed crawlspaces are bad for airflow. If crawlspaces must be used, they should be open. The mechanical method, forced ventilation or artificial cooling, must have reliable power for it to operate as intended (Darrow & Jensen, 2016). Common mechanical cooling methods are geothermal heat pumps or crawlspace ventilation (Darrow & Jensen, 2016; Scher, 1991). A danger to this method is that cooling the ground past its natural temperature may cause adverse damage by accelerating the heaving process (Scher, 1991). To cost effectively use a mechanical system, the owner/user needs to consider the additional cost of equipment, maintenance, and personnel.

PACAF will not circumvent the mission priorities due to the presence of discontinuous permafrost (United States Pacific Command, n.d.). Beddown efforts for mission critical assets will drive the demand for construction on permafrost. Planning for multiple beddown sites of a building increases time, resources, and availability of funds to the DoD. Proper site investigation and information on how to handle a certain quantity of permafrost gives both the user and contractor a better understanding of what needs to be done to build a permanent structure.

In the lower 48 states, structural loading (mostly vertical) is transferred through the foundation to the bearing ground. In a region where permafrost and deep seasonal freeze occurs, the interaction of loads changes drastically (Shiklomanov et al., 2017; Widianto et al., 2015). Frost heaving is capable of damaging buildings due to the interaction of soil saturation and the superstructure (Bell & Ashwood, 2016; Clarke, 2007; Widianto et al., 2015). This generates subsurface pressure forcing the building to shift upwards in an expansion/contraction motion (UFC3-110-03, 2004). To prevent excess heaving through thermal variations in the winter, a building's foundation should be closed in and interior heat turned on (Nash, 2009).

Differential settlement occurs when a foundation sinks into the ground at an uneven rate compared to other sections of the foundation. This takes place when the soil's bearing capacity decreases and cannot hold the weight of the structure it was once supporting (Lewkowicz et al., 2016; Muller, 2008). Most of a building's heat intensity is kept at the floorplan's center and dispelled towards the edges (Shankle, 1985). This means that a bulb-shaped thaw pattern forms underneath the foundation (Shankle, 1985). This type of pattern creates a progressively faster settlement issue for the interior portion of the foundation than the exterior, which causes a sunken floor inside the building (Shiklomanov et al., 2017). In all permafrost regions, this occurs when the thawing process starts. This type of damage increases maintenance costs through structural repair and may cause hardship for personnel and the mission housed inside. To counteract differential settlement through the thawing process, the foundation must be designed and constructed even deeper into the soil, below the stationary thaw basin and active layer (Department of Defense, 2004; Shiklomanov et al., 2017; Widianto et al., 2015; Yershov, 1998). This increases the cost of the foundation and earthwork required for the building because of the additional materials required to construct this type of design (Shankle, 1985; Yershov, 1998).

Over the years, both the private and public sectors have considered different foundation designs and construction techniques to effectively execute them in the arctic region. The design and construction of a building is developed in regards to multiple factors including but not limited to site data, environmental criteria, cost restraints, facility requirements, maintenance requirements, thermal calculations, reliability of power, and intended use (Shankle, 1985). The remaining portion of chapter discusses the different foundation types used in the region to combat the presence of permafrost, frost heaving, and differential settlement.

2.4 Fairbanks Area Soil Composition

The two main military bases near Fairbanks are Eielson Air Force Base (AFB) and the Army's Fort Wainwright ("Alaska Military Bases," 2017). Fort Wainwright is located within Fairbanks' city limits and has little space to expand, if required. The fort has a natural border to the north, east, and west – the Chena River. Eielson AFB can expand in any direction, except to the west where it borders the Richardson Highway. Eielson AFB and Fort Wainwright have similar soil composition that is detailed in Appendix A and B, respectively. Most of soil is classified as a type of "Urban Land," meaning that the area is mostly covered by streets, roads, buildings, or other structures (United States Department of Agriculture, 2016, 2017).

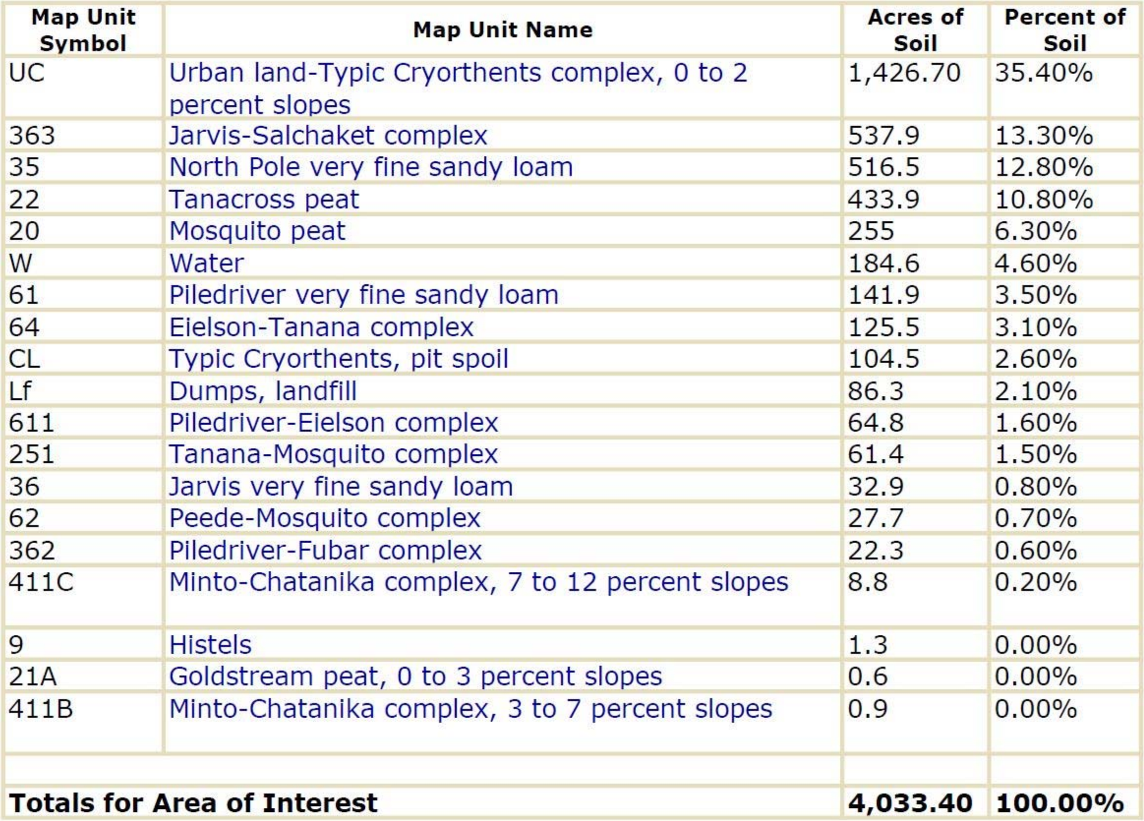
Table 1. Eielson AFB 2015 Soil Survey Samplesdetails Eielson AFB's most common soils. The three most common soils after the dominated "Urban Land" are Jarvis-Salchaket complex (13.30%), North Pole very fine sandy loam (12.80%), and Tanacross peat (10.80%). The remaining soils have total percentages ranging from 0.2-6.3% (United States Department of Agriculture, 2017). Jarvis-Salchaket complex soil is classified as well drained, with a low water table (72+ inches) and stratified layers of silt

loams to fine sands (United States Department of Agriculture, 2016). This type of soil is favorable compared to the other leading soils in the area. Its high water table limits the damage done through frost heaving and the creation of permafrost.

The North Pole soil is classified as a very fine sandy loam with poor drainage, a very high water table (0-8 inches), and concentrations of decomposed organic matter (United States Department of Agriculture, 2016). Defined as a high permeability soil, the use of this soil is limited. Pockets of organic matter can be found throughout the layers, thus creating issues with settlement and frost heaving.

Tanacross peat soil contains a majority of organic matter that leads to poor drainage and a non-existent water table (0 inches) (United States Department of Agriculture, 2016). This type of peat floods and ponds frequently. It is also the only soil that has management considerations due to it be susceptible to permafrost (United States Department of Agriculture, 2016). This is mostly due to the high concentrations of organic matter and the ability to form permafrost from a depth of 10-28 inches (United States Department of Agriculture, 2016).

Table 1. Eielson AFB 2015 Soil Survey Samples (United States Department of Agriculture, 2017)



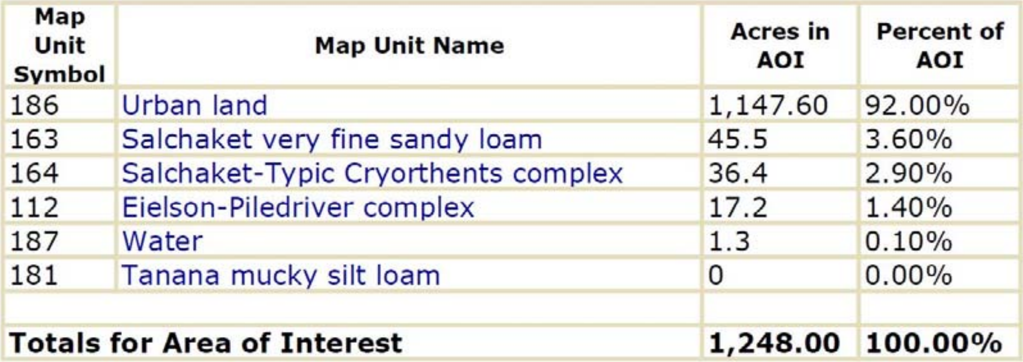
Map Unit Symbol	Map Unit Name	Acres of Soil	Percent of Soil
UC	Urban land-Typic Cryorthents complex, 0 to 2 percent slopes	1,426.70	35.40%
363	Jarvis-Salchaket complex	537.9	13.30%
35	North Pole very fine sandy loam	516.5	12.80%
22	Tanacross peat	433.9	10.80%
20	Mosquito peat	255	6.30%
W	Water	184.6	4.60%
61	Piledriver very fine sandy loam	141.9	3.50%
64	Eielson-Tanana complex	125.5	3.10%
CL	Typic Cryorthents, pit spoil	104.5	2.60%
Lf	Dumps, landfill	86.3	2.10%
611	Piledriver-Eielson complex	64.8	1.60%
251	Tanana-Mosquito complex	61.4	1.50%
36	Jarvis very fine sandy loam	32.9	0.80%
62	Peede-Mosquito complex	27.7	0.70%
362	Piledriver-Fubar complex	22.3	0.60%
411C	Minto-Chatanika complex, 7 to 12 percent slopes	8.8	0.20%
9	Histels	1.3	0.00%
21A	Goldstream peat, 0 to 3 percent slopes	0.6	0.00%
411B	Minto-Chatanika complex, 3 to 7 percent slopes	0.9	0.00%
Totals for Area of Interest		**4,033.40**	**100.00%**

Fort Wainwright's soil survey, shown in Table 2, is not detailed as the area surrounding Eielson AFB because of the lack of available expansion. Most of the soil (92.00%) is classified as "urban land." Salchaket very fine sandy loam 3.60% of the soil; it takes on the same characteristics as North Pole very fine sandy loam and is mostly found in the flood plain areas (United States Department of Agriculture, 2016). This is consistent since Fort Wainwright is surround by the Chena River on three sides.

Salchaket-Typic Cryorthents complex, representing 2.90% of the soil, drains well with a low water table of 72+ inches (United States Department of Agriculture, 2016).

This high gravel content soil has some construction limitations, including minor flooding and ponding due to the organic matter (United States Department of Agriculture, 2016). The last soil worth noting is the Eielson-Piledriver complex. Flooding and ponding is common with this soil because of the negligible runoff characteristics associated with it (United States Department of Agriculture, 2016). With this soil, frost action is the biggest concern.

Table 2. Fort Wainwright 2015 Soil Survey Samples (United States Department of Agriculture, 2017)



Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
186	Urban land	1,147.60	92.00%
163	Salchaket very fine sandy loam	45.5	3.60%
164	Salchaket-Typic Cryorthents complex	36.4	2.90%
112	Eielson-Piledriver complex	17.2	1.40%
187	Water	1.3	0.10%
181	Tanana mucky silt loam	0	0.00%
Totals for Area of Interest		**1,248.00**	**100.00%**

2.5 Pile and Pier Foundations

Pile foundations are a type of deep foundations with post-like members that are placed in a column-row formation to support a structure placed above them (No & Washington, 2011). In modern history, piles are comprised of timber, steel, or concrete and constructed using different methods depending on the soil composition at the building site (Neukirchner & Asce, n.d.; No & Washington, 2011; Wang, Zhang, & Na, 2017; Weaver & Morgenstern, 1981). The installation of concrete piles includes cast-in-place or precasted concrete, which is then lowered into the borehole and backfilled if required. Timber piles are tapered with the smaller diameter end thrusted into the ground to form a cylindrical wedge; steel piles are forced into the ground through impact, vibratory, or sonic hammers (Heydinger, 1987; Neukirchner & Asce, n.d.). To increase the effectiveness of piles, the use of spikes protruding from timber piles, welding steel plates to the beam to act like anchors, or using other techniques that increases soil adhesion by maximizing the piles grip and surface area is common (Heydinger, 1987). Piers are comparable to pile foundations except that the pier style extends past the surface level to form a raised slab. In Alaska, pier foundations could function for a building's crawlspace that utilizes the natural or forced convection under the structure, as mentioned previously.

There are other options available when designing piles for permafrost, but they are not as widely sought after in discontinuous permafrost. Helical piles or screw piles, shown in Figure **4**, are typically made of steel with a tapered end to allow for better installation (Mohajerani, Bosnjak, & Bromwich, 2014). As discussed in the advantage section of pile foundations, screw piles do not require grout to fill voids and the flanges of the screw shape act as anchors for the active freeze-thaw layer (Mohajerani et al., 2014). If the soil is rocky, helical piles require a more tapered end to improve the passage through rocks (Arup Geotechnics, 2005).

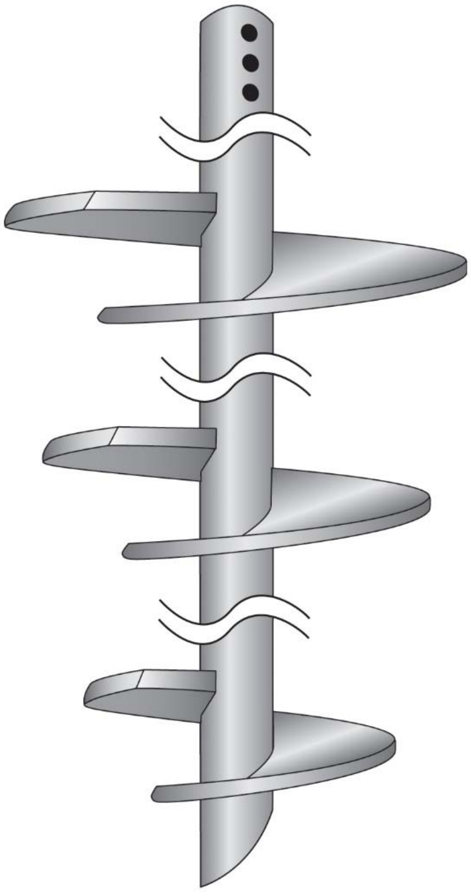
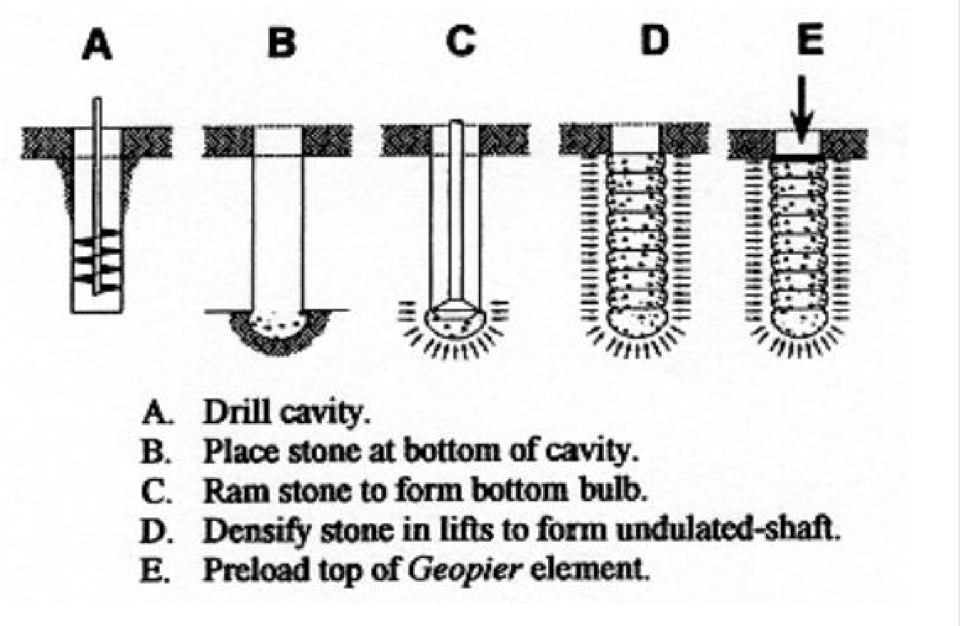


Figure 4. Helical Pile (Earth Contract Products, 2009)

The last form of piles has taken off in the drier climates of the lower 48 states. Specifically in California, geopiers are used to replace the traditional concrete and steel piles (Fox, Weppler, & Ingenieure, 2001). Figure **5** showcases the geopier installation process by compacting crushed aggregate piles purely serving the vertical load (American Society of Professional Estimators, 2010). Serving as strictly a vertical load, it exposes the potential problems when using geopiers in permafrost conditions. Since geopiers only support vertical loads, the freeze-thaw active layer will destroy the crushed aggregate and leave each pile in a loose state.



A. Drill cavity.
B. Place stone at bottom of cavity.
C. Ram stone to form bottom bulb.
D. Densify stone in lifts to form undulated-shaft.
E. Preload top of *Geopier* element.

Figure 5. Geopier Condensed Installation Guide (American Society of Professional Estimators, 2010)

2.5.1 Advantages of Traditional Pile and Pier Foundations

The void between the borehole and pile is filled with mud or cement grout, which acts as additional insulation (Heydinger, 1987; UFC3-110-03, 2004). Utilizing black polyethylene film around the portion of pile subject to the active layer reduces the adfreeze grip, which reduces the frost heaving forces (McFadden, 2001). This benefit helps in maintaining strict building tolerances that the mission requires.

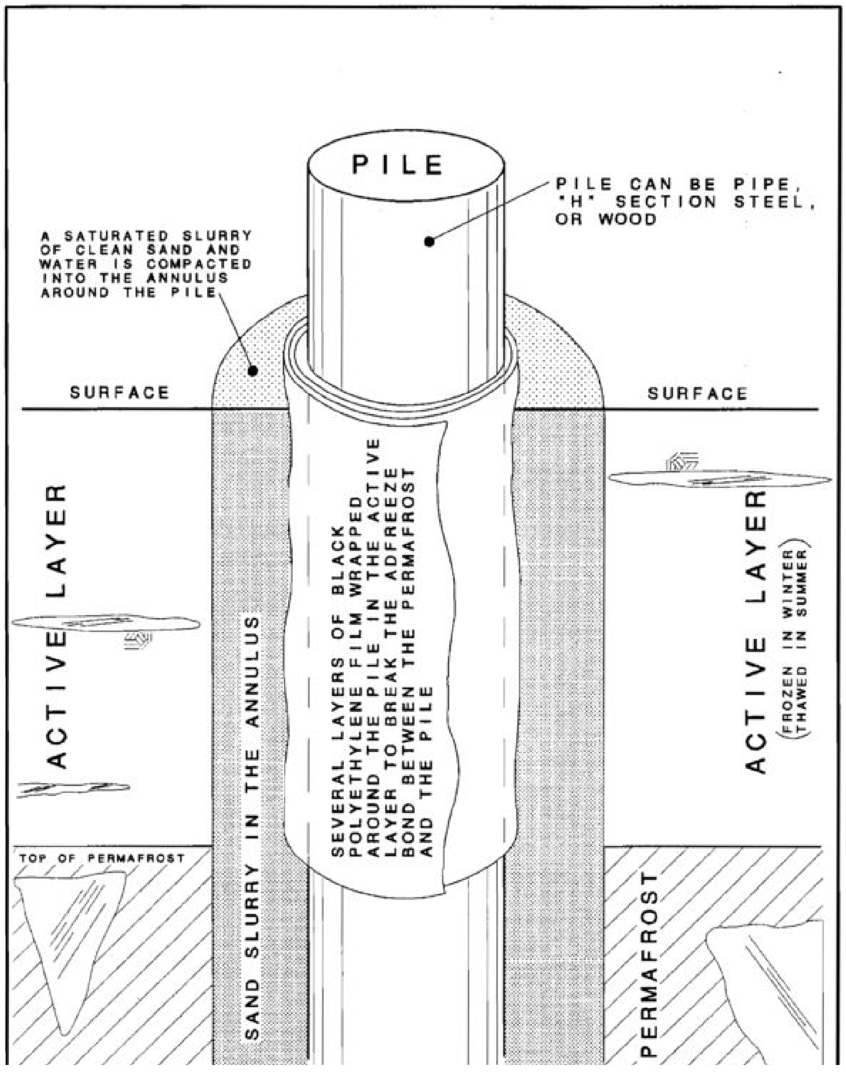


Figure 6. Pile with polyurethane sleeve (Heydinger, 1987)

2.5.2 Disadvantages of Pile and Pier Foundations

Though common in the permafrost region, this type of foundation is not without fault. Frost heaving is a major destructive factor in colder climates, especially with these foundation types (Ferrians et al., 1969; McFadden, 2001). The problem lies with keeping the columns in the ground because of the tremendous force displacing the columns upward, based on the active layer's thickness (Ferrians et al., 1969). The displacement is usually at different rates between each pile/pier due to soil composition, ice, and mean temperature (US Army Corps of Engineering, 1950; Weaver & Morgenstern, 1981). Alaskan timber piles are sometimes inverted (the side with the larger diameter is at the bottom of the borehole) to prevent the enormous forces from pushing the pile out (Li & Yang, 2017). To counteract these forces, the foundation needs to be placed even deeper into the ground, which drives up cost in terms of equipment, materials, and labor (Ferrians et al., 1969). Pier foundations have a unique set of challenges. They require lateral load calculations based on the height protruding from the soil surface (Mu et al., 2017).

2.6 Convection to Maintain Permafrost

Permafrost preservation is the second ideal way of designing and constructing in the northern tier region (Darrow & Jensen, 2016; Geoslope International Inc., 2000; Jensen, 2015; Yershov, 1998). Man-made structures alter the environment's delicate thermal balance, and convection methods promote the preservation in a controlled fashion (Darrow & Jensen, 2016; Geoslope International Inc., 2000).

2.6.1 Passive Convection

Passive convection, also known as passive cooling or refrigeration, is the use of an air barrier between the building and the ground or the use of geothermal energy transfer (Darrow & Jensen, 2016; Geoslope International Inc., 2000; Perreault & Shur, 2016). Both methods do not require a reliable power source to function (Shankle, 1985; Yershov, 1998).

The air barrier method, depicted in Figure **7**. Gravel Pad Foundation , uses either an empty void underneath the structure, usually a crawlspace, or a highly porous material as a shallow foundation (Geoslope International Inc., 2000; Grebenets et al., 2014; Jensen, 2015). Crawlspaces, without obstructed ventilation, allow natural wind currents to cool the surrounding building before disrupting the soil's equilibrium – if the right conditions are met (Jorgenson et al., 2008; Nash, 2009; Xu & Goering, 2008).

Figure 7. Gravel Pad Foundation (Cedar Built, 2015)

Highly porous materials have their own exclusive role in permafrost regions. The material is mostly used on smaller, lighter structures or on public infrastructure, like roads. The chosen gravel must perform well under all conditions at the proposed site (Geoslope International Inc., 2000; Haeberli, Whiteman, & Shroder, 2015).

The use of geothermal energy transfer is easily achieved by one- or two-phase thermosyphons surrounding the proposed building (Scher, 1991; Xu & Goering, 2008; Yarmak & Farmwald, 1993). If the building needs to be at-grade and on a large percentage of permafrost, then subgrade cooling might be appropriate to stay within budget for the project (Fauske, Parnell, Blumer, & Robinson, 2014; Scher, 1991). Figure **8** and Figure **9** display this type of installation for both at-grade and pier foundations. Two-phase thermosyphons are preferred over the other types of subgrade cooling technology. Thermosyphons transfer heat against gravity (Pei et al., 2017; Yarmak & Farmwald, 1993; Yu et al., 2016). The condenser is installed above ground while an enclosed pipe is filled with propane, butane, CFCs, HCFCs, anhydrous ammonia, or carbon dioxide at a temperature lower than the soil's to jumpstart the evaporation cycle (Guo et al., 2016; Xu & Goering, 2008; Yarmak & Farmwald, 1993). Low maintenance geothermal energy transfer methods are effective in some given scenarios.

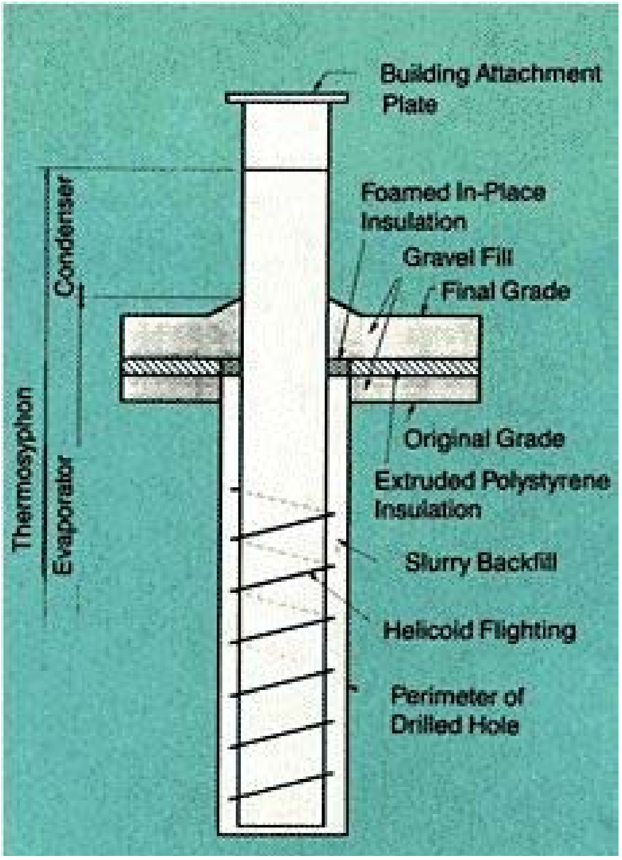


Figure 9. Passive pile convection coil (Yarmak, 2015)

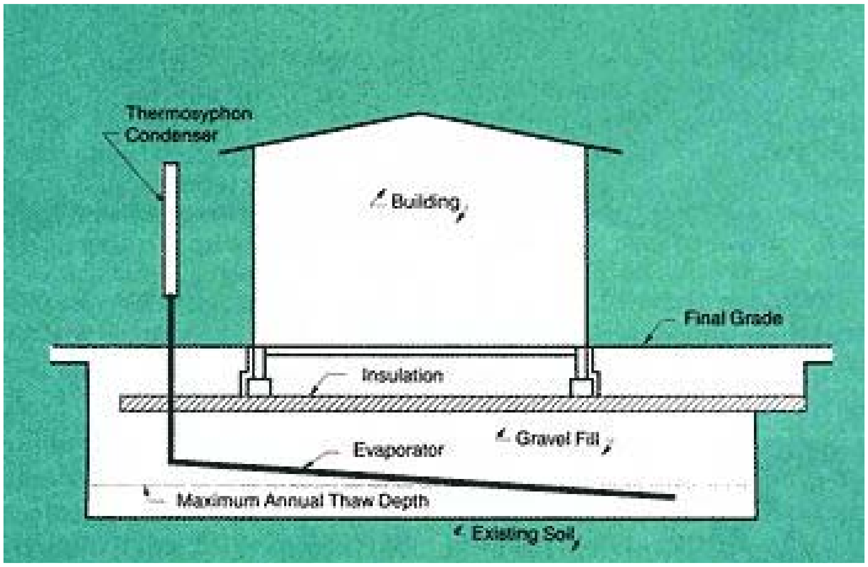


Figure 8. Two-phase thermosyphon at grade level (Yarmak, 2015)

2.6.2 Advantages of Passive Convection Systems

These standalone refrigeration systems operate at a minute maintenance cost because of the lack of power required to operate them (Geoslope International Inc., 2000; Krzewinski et al., 2013). Crawlspaces require pier foundations that are easily designed, and thermosyphons require specific angles that most larger buildings can accommodate (Darrow & Jensen, 2016). Cost and ease of use of crawlspaces are the more desirable traits regarding the passive convection systems. Subgrade cooling can potentially increase the strength of the permafrost by lowering the soil's temperature and effectively solidifying it (Yarmak & Farmwald, 1993). In Kotzebue, Alaska, a project was deemed successful at permafrost preservation when an eight-acre hospital was erected with only 23 thermosyphons drilled to varying depths of 11 to 30 meters (35 to 101.5 feet) (Yarmak & Farmwald, 1993).

2.6.3 Disadvantages of Passive Convection Systems

For crawlspaces, depending on the thermal balance, the space between the structure may vary between one and two meters (3-6 feet), thereby demanding more lateral load support for required pier foundations (Shankle, 1985; Yarmak & Farmwald, 1993). The porous material route increases the cost of additional materials and transportation to the site. This could dissuade designers if the location is remote and local materials do not meet specifications. Another problem with porous material is the low angled slope required to maintain the loading capacity of the building (Geoslope International Inc., 2000).

2.7 Forced Convection

When the building cannot be raised to utilize natural convection, or the building's thermal loading is greater than maximum crawlspace height, forced convection is another great alternative solution to keeping the permafrost in its natural state (Pei et al., 2017; Scher, 1991; Yu et al., 2016). Fans or blowers are suitable for maintaining the delicate balance when colder outside air is introduced to the enclosed crawlspace area (McFadden, 2001). They will need specialized design to effectively maximize air flow configuration (Jørgensen, Doré, Voyer, Chataigner, & Gosselin, 2008; Scher, 1991). The number of openings is dependent on the size and shape of the building’s crawlspace (McFadden, 2001). Openings should come in pairs, shown in Figure **10**, so the same number of intake openings match the exhaust openings (McFadden, 2001). With these systems, a smart fan controller can be installed inside the building to regulate the temperature without constant human interaction (Darrow & Jensen, 2016). During the summer months, the forced convection system will not be used, but during the winter months it will most likely be constantly running (Hayley, 1982).

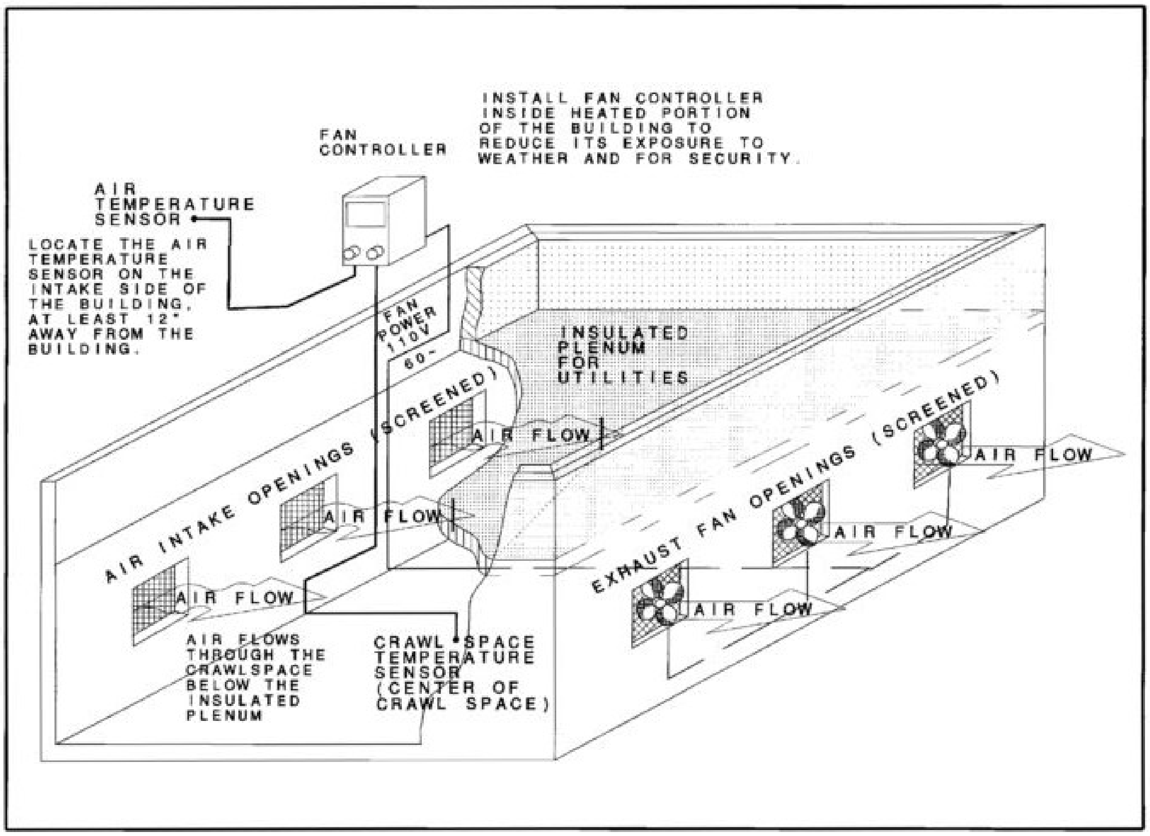


Figure 10. 3D model of forced convection using fans (McFadden, 2001)

2.7.1 Advantages of Forced Convection Systems

This proactive artificial cooling system allows the users to control the thermal balance in the crucial winter months when the building's thermal discharge will be the highest. This versatile system is a candidate for any building with a crawlspace of any height – as long as it provides the desired cooling effect (Haeberli et al., 2015; Shang, Niu, Wu, & Liu, 2018). The consequence of a system or power failure must be weighed with respects to the sensitivity to settlement (Hayley, 1982; Shankle, 1985).

2.7.2 Disadvantages of Forced Convection Systems

Introducing supplementary equipment to a building will certainly drive up the maintenance cost and the number of personnel (Krzewinski et al., 2013; Zhang, Pei, Lai, Niu, & Li, 2017). An evaluation will be required to see if current manning levels are effective for this system. Fans or blowers are only effective when the exterior temperature is cooler than the interior crawlspace temperature (McFadden, 2001). There is a requirement to have a secondary crawlspace, an insulated plenum, for freeze sensitive utility lines (sewer, water, or raised flooring HVAC systems) if fans and blowers are to be used (Shankle, 1985; Shiklomanov et al., 2017).

2.8 Limited Labor Pool of Alaska

The state of Alaska is the largest state by land mass, but it is 48th out of 50 when it comes to population (U.S. Census Bureau, 2010, 2016). This leaves a little to be desired when it comes to the working force of the state. With an estimated population of 741,952, only about 47% of the population are within the ages of 18 and 65 (U.S. Census Bureau, 2016, 2017). Looking at the job "construction laborers," only 7,365 residents have that title and fill the requirements set by the state (Alaska Department of Labor and Workforce Development, 2016b). Construction labor involves physical labor, equipment operation, surveying and measuring, site prepping, trenching, excavations, concrete mixing, and general site cleanup (Alaska Department of Labor and Workforce Development, 2016b; Bureau of Labor Statistics, 2016). With a very limited job pool to choose from within the state, it does not help that 25.3% of construction laborers are above the age of 45 (Alaska Department of Labor and Workforce Development, 2016b).

This limited workforce is reflected by the short list of businesses that can perform these types of jobs.

Designing and developing all the construction for the state is up to the 983 civil engineers in the state (Alaska Department of Labor and Workforce Development, 2016a). However, 45.8% of the civil engineers are above the age of 45 (Alaska Department of Labor and Workforce Development, 2016a). The high percentage of civil engineers are within retirement age in 15 years, potentially removing almost half of the knowledgeable design experts.

Comparing Alaska's construction labor workforce to Washington State, the difference in opportunity and free market competition can be seen. Washington State has a population of 6.7 million and a construction labor workforce of 114,700 (Bureau of Labor Statistics, 2016). With the drastic increase in both population and workforce comes job opportunity for all the businesses within the market. This large competition spills over to Alaska but adds materials and manufacturing bulk items for Alaska's construction needs (Butcher, Whitney, Krieger, Weibold, & Dusenberry, 2016).

2.9 Cost Considerations of Alaska

The cost of doing business is dependent on the market. When this logic is applied to remote areas of Alaska, this can increase the cost of construction dramatically. This is compounded by Alaska's unique permafrost situation that is not found anywhere else in the United States (NSIDC, n.d.). DoD's Tri-Service Cost Engineering Steering Committee (TSCESC) analyzes the construction market annually at 390 CONUS (a minimum of 2 cities per state) and 83 OCONUS (Outside Continental United States) locations (Department of Defense, 2017). At the end of their research, they develop an Area Cost Factor (ACF) that government agencies can apply to their unit price and line items to account for the difference in labor, materials, equipment, and services. As of 28 March 2017, TSCESC reformed the scale setting the national cost average to 1 and ranges between 0.79 and 4.69 (Department of Defense, 2017). Fairbanks, Alaska, has an ACF of 2.27; however, even though their proximity to Fairbanks is minimal, Fort Greely, Fort Wainwright, and Eielson AFB all operate at slightly higher factors of 2.51, 2.33, and 2.35, respectively (Department of Defense, 2017). This is corroborated by Alaska Department of Labor and Workforce Development's yearly survey to identify the trends in construction throughout the state's urban and rural areas.

Alaska pays an average of 43% more in materials than its closest U.S. neighbor, Washington State (Butcher et al., 2016). Fairbanks, in particular, shows an increase of 1% to 14% per year since 2012 (Butcher, Whitney, Krieger, Weibold, & Dusenberry, 2015). The cause of this could be urban development for the area and the news of having additional military presence in the local community. The most common items for large scale construction are concrete and rebar. Fairbanks pays a premium for rebar: an average of $7.43 per #4 at 20-foot length (Butcher et al., 2016). In California, where construction is more constant, a #4 rebar only costs $4.95 per 20-foot section (WC Rebar, 2018). For concrete, Fairbanks is estimated to pay $112 per cubic yard (Butcher et al., 2016; Fauske et al., 2014). The most recent National Ready Mixed Concrete Association (NRMCA) survey listed the national average of concrete to be $98 per cubic yard

(National Ready Mixed Concrete Association, 2014). The annual ACF report and Construction Cost Survey both stated that the increase in labor, construction schedule, or natural disasters changes the ACF due to supply and demand. Construction materials may not be available at the time required for emergent needs. If the request of construction is beyond what the local market can handle, then increases in cost, through incentive pay, premium pay, overtime, living expenses, or travel expenses should be considered (Department of Defense, 2017). Eielson AFB is overseeing the beddown of the F-35, which is abnormally large for the region (United States Pacific Command, n.d.). This will be the first of many steps to ensure the safety and viability of PACAF's regional mission. Other large new construction, renovations, or repair projects could see increased costs from local vendors if not planned or scheduled properly for the market.

Alaska will always pay a premium for materials because of the location. That is why over the years 2012-2016, Fairbanks paid between 22% and 30% more on materials shipped in from Seattle, Washington (Butcher et al., 2016; Fauske et al., 2014). When it comes to concrete, Fairbanks has the lowest prices in Alaska because the city is centralized in one of the highest populated areas (Fauske et al., 2014). Since Fairbanks is in the discontinuous permafrost region, the cost of concrete construction may be skewed compared to other discontinuous permafrost regions of the world.

2.10 Summary

All these different systems must overcome the two most destructive factors when building on permafrost: frost heave and differential settlement. These issues are compounded in discontinuous permafrost due to the varied depths and locations. The use of both permafrost construction techniques described by Yershov (1998) will allow the designer and user to alleviate time and cost factors to determine the best superstructure for specific areas in the northern tier region. Building on permafrost has two solutions: 1) remove all existing permafrost or 2) preserve the permafrost in its natural state. Both of his options require supplementary resources to achieve, either through increased amounts of replacement soil or through maintenance (Melvin et al., 2017; Yershov, 1998). Likewise, Shankle (1985) understood the catastrophic damage that may occur when constructing on both types of permafrost. His logic appeared through the lens of life-cycle. In the DoD, most CONUS (Continental United States) military bases construct permanent structures for their missions – Alaska is no different. Shankle (1985) addressed the criteria and differing techniques to achieve both permanent (25 to 30 years) and temporary (1 to 5 years) structures. Discontinuous permafrost is volatile, and all methods addressed have their place in Alaskan construction. However, the main focus of this research will be on total replacement or incorporating permafrost into the design.

III. Methodology

The research will be based on a project that the researcher creates. It will be simplified to the three main factors that were described in previous chapters. The occupational use will dictate the size and loading of a facility. The amount of permafrost determines appropriate foundations methods to implement in region. The third factor, depth of the foundation, controls the cost of the earthwork portion of the cost estimate.

3.1 Methodology for Basic Cost Estimates

This section of the chapter will be the development of a fictitious project. The project will be what the researcher discussed with the experts working in Alaska.

3.1.1 Qualifications of Experts

Experts in the region defined as members of the construction community that have business stakes in the researcher's fictitious project. The experts were identified to have more than 10 years of experience in their fields and have done work for the DoD directly or through sub-contracts. The experts were integral to the research; they come from excavation companies, concrete manufacturers, engineering firms, and construction management firms.

3.1.2 Development of the Fictitious Project

To get an accurate costs from the experts, the researcher used a fictitious aircraft hangar to gauge the responses and cost estimates provided by the experts. The aircraft hangar was loosely based on the information provided by Schweiss' online catalog. The hangar for the C-130 Hercules is identified to be 150' L x 200' W x 50' H (Schweiss, 2017). These dimensions were simplified even further to create a facility that was 200’ L x 200’ W x 50’ H. This was done by the researcher to include testing space, additional storage, and accompanying offices. The mathematical calculations to determine the volume of soil and piles can be found in Appendix C.

As discussed in Chapter II of this thesis, the price of concrete is fairly cheap in Fairbanks, Alaska. The price of transportation and labor is extraordinarily high, which drives the price per CY dependent on location. For this research, the location of the site is Eielson AFB, which is 25 miles away from Fairbanks. With a transportation index for the surrounding area of Fairbanks at 120, a multiplier of 20 was be added to the cost of concrete portion of the data (Butcher et al., 2016).

3.1.3 Bearing Capacity of the Soil

Understanding bearing capacity and the amount of weight soil can handle before developing shear failure is fundamental for designing a foundation. In Alaska, permafrost can make designing a foundation harder through its random location and variable properties. Specifically, the city of Fairbanks has taken the International Building Code (IBC) and refined some of the sections for engineers in the region. The amendments to the IBC includes a blanket statement that the bearing capacity of soil should not be greater than 3,000 pounds per square foot (PSF) (City of Fairbanks, 2015). The IBC does not have a maximum bearing capacity value for general soils. Instead, Table 1804.2 dictates allowable pressure based on the classification of soil (International Building Code, 2015). Soils in Fairbanks are mostly silty sands and silty gravel, for which the IBC recommends a maximum strength of 2,000 PSF (International Building

Code, 2015). The discrepancy between the city of Fairbanks and the IBC comes down to not fully understanding what else is beneath the soil. Alaska has to deal with permafrost and a large amount of water from rain and melting snow. These challenges make Fairbanks unique. No matter the soil condition, a maximum of 3,000 PSF can be used to help prevent damages due to permafrost or other unknown soil conditions (City of Fairbanks, 2015).

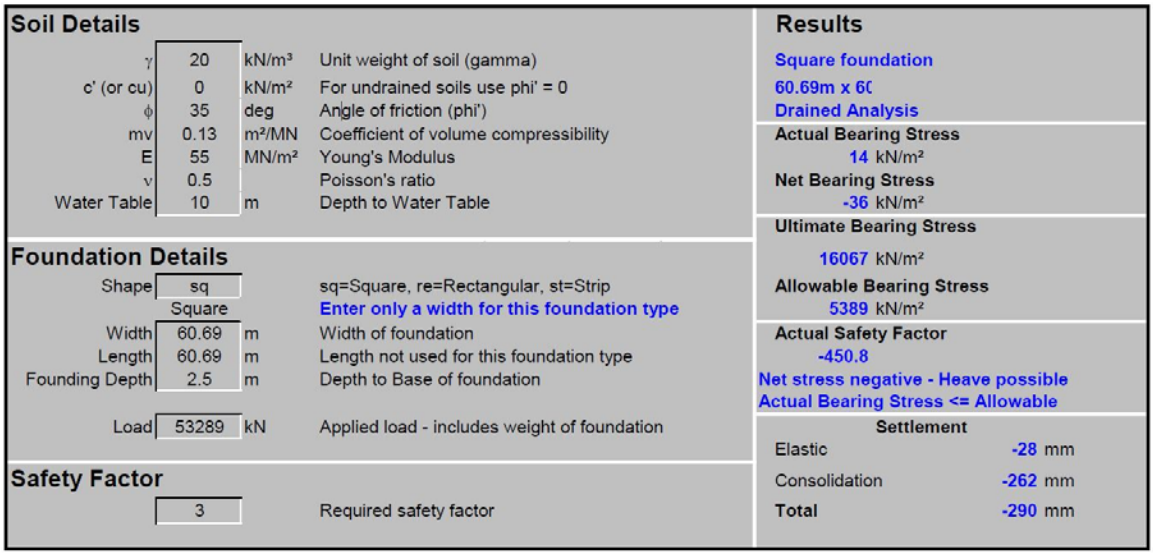
Appendix C has all the equations regarding the development of the number of piles used in the creation of the fabricated project. The research used University of the West of England's (UWE) Excel Foundation Calculator to determine the soil minimum capacity to support the aircraft hangar (University of the West of England, 2012).

UWE is a leader in the environmental industry. They are accredited through seven different programs including: the Royal Institution of Chartered Surveyors (RICS), Chartered Association of Building Engineers (CABE), and Chartered Institution of Civil Engineering Surveyors (ICES) (University of the West of England, 2018). This portion of the postgraduate institution advises 70% of the built environment sector (University of the West of England, 2018). They also work closely with 25 different industry leaders to help focus research on problems from around the world (University of the West of England, 2018).

Due to the varying soils in the area, the researcher used the most common soil surrounding Eielson AFB, Jarvis-Salchaket complex, for the bearing capacity calculations. Table 3 are the variables that were inserted into UWE's bearing capacity calculator. Since this soil contains organic matter able to drain well, the unit weight (γ)

of this soil classification can reach anywhere between 15-20 kN/m^3 (American Society of Agricultural and Biological Engineers, 2009). The angle of friction (φ) was set to 35° because of the composition of the soil (American Society of Agricultural and Biological Engineers, 2009). The high permeable soil also has a low water table; the researcher used a depth of 12 ft (3.66 m) for calculations. The Factor of Safety (FS) used for this was also set to 3; this was due to the variability in soil. The last portion of the calculation is determining the load of the structure. Based on the weight of one fully stocked C-130 (83,000 lbs), aircraft hangar (85 PSF), office space (50 PSF), equipment (25 PSF), and other miscellaneous weather loads (40 PSF), the total dead and live loads equals 11,980,000 lbs (53,289 kN) (Schweiss, 2017; Simpson, 2014). The live loads associated with this calculation have a FS of 1.7 and dead loads of 1.4 (International Code Council, 2016; *Loads on Buildings and Structures*, 2012). After computing all the numbers, the Ultimate Bearing Capacity is 335,566 PSF (16,067 kN/m^2) (University of the West of England, 2012). This is the maximum weight the soil can withstand before failing.

Table 3. Bearing Capacity Calculation (University of the West of England, 2012)



Soil Details

γ	20	kN/m³	Unit weight of soil (gamma)
c' (or cu)	0	kN/m²	For undrained soils use phi' = 0
ϕ	35	deg	Angle of friction (phi')
mv	0.13	m²/MN	Coefficient of volume compressibility
E	55	MN/m²	Young's Modulus
ν	0.5		Poisson's ratio
Water Table	10	m	Depth to Water Table

Foundation Details

Shape	sq		sq=Square, re=Rectangular, st=Strip
	Square		Enter only a width for this foundation type
Width	60.69	m	Width of foundation
Length	60.69	m	Length not used for this foundation type
Founding Depth	2.5	m	Depth to Base of foundation
Load	53289	kN	Applied load - includes weight of foundation

Safety Factor

	3		Required safety factor

Results

Square foundation
60.69m x 6(
Drained Analysis

Actual Bearing Stress
14 kN/m²
Net Bearing Stress
-36 kN/m²

Ultimate Bearing Stress
16067 kN/m²
Allowable Bearing Stress
5389 kN/m²

Actual Safety Factor
-450.8
Net stress negative - Heave possible
Actual Bearing Stress <= Allowable

Settlement

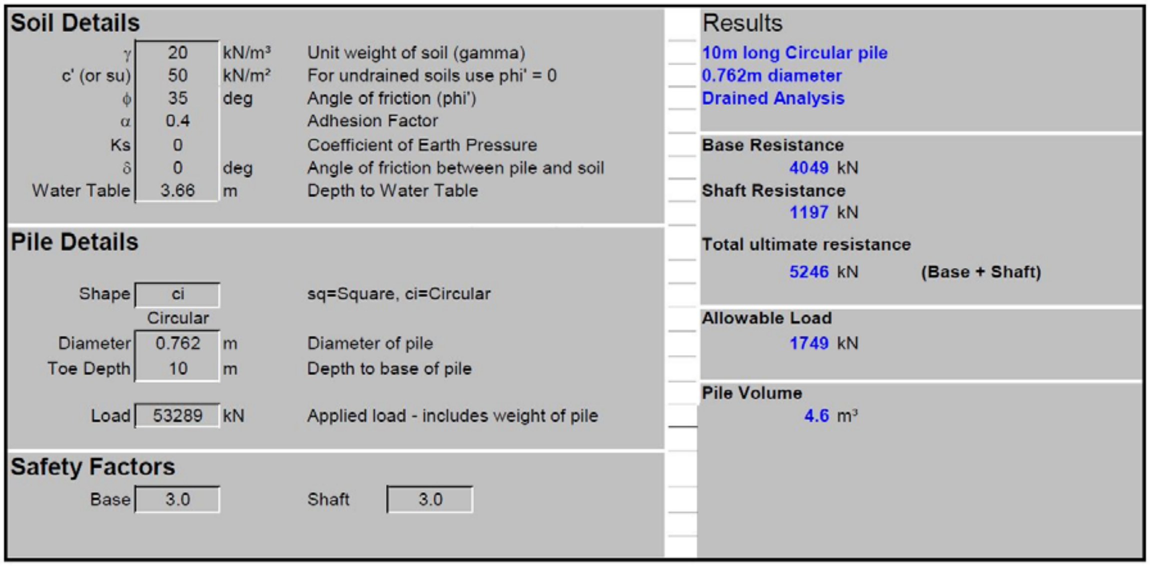
Elastic	-28	mm
Consolidation	-262	mm
Total	-290	mm

3.1.4 Number of Required Piles

The final step in determining the number of piles is to figure out how many piles it takes to counteract the ultimate bearing capacity. The calculation was done through UWE's Excel Pile Calculator. The soil coefficients used in this equation represented the Jarvis-Salchaket complex. Since details are not provided in the most recent Greater Fairbanks soil survey, the researcher adopted the use of the general classification of a silt load. UWE's calculator requires the cohesion of soil (c') to measure the strength of each pile. Adopted from the general soil classification, silt loam has a cohesion between 10-90 kPa (10-90 kN/m^2) (Geotechdata.info, 2014). This depends on compaction and saturation levels; the research used a value of 50 to represent a well-drained soil that has little to no compaction. Since using a general soil classification, an increased FS from 2 to 3 was used to ensure a safe pile capacity. All other data regarding the soil were the same as the bearing capacity calculations. Table 4 has all the pertinent information regarding this process. After inputting the correct variables, each pile can carry 393,190 lbs (1,749 kN) (University of the West of England, 2014).

The researcher can now divide the load of the pile to the weight of the total structure. With that information, the fictional project will need a minimum of 30.46 piles. Because the building’s footprint is square, a total of 36 piles was utilized. This is so the facility can maintain a 6x6 pile grid. The analysis made the baseline per pile price to be equal to 36 piles. Additional piles will increase the base price; fewer piles will decrease the base price of each pile.

Table 4. Pile Capacity Calculation (University of the West of England, 2014)



Soil Details

γ	20	kN/m³	Unit weight of soil (gamma)
c' (or su)	50	kN/m²	For undrained soils use phi' = 0
ϕ	35	deg	Angle of friction (phi')
α	0.4		Adhesion Factor
Ks	0		Coefficient of Earth Pressure
δ	0	deg	Angle of friction between pile and soil
Water Table	3.66	m	Depth to Water Table

Pile Details

Shape	ci Circular		sq=Square, ci=Circular
Diameter	0.762	m	Diameter of pile
Toe Depth	10	m	Depth to base of pile
Load	53289	kN	Applied load - includes weight of pile

Safety Factors

Base 3.0 Shaft 3.0

Results

10m long Circular pile
0.762m diameter
Drained Analysis

Base Resistance
4049 kN
Shaft Resistance
1197 kN
Total ultimate resistance
5246 kN (Base + Shaft)

Allowable Load
1749 kN

Pile Volume
4.6 m³

3.1.4 Assumptions of Data

The hangar model used in the calculations were presented to all the experts. Some assumptions were made during the process of creating the project. This was to simplify the incoming data, because effective designs vary for all construction sites. The four main assumptions were:

1. Excavation site is in an open area allowing for the use of sloping and benching
2. There are no contingency funds for the project
3. Soil at the proposed site was primarily Jarvis-Salchaket complex
4. The travel distance from to contractor to site is: 25 miles

The first assumption is put into place to constrain the researcher from other costs associated with benching and sloping. The second assumption was aimed to provide a more accurate estimate from experts. It forced the experts to critically think about how much they would charge for materials and labor for a job this size. The third assumption was based on soil surveys conducted by the United States Department of Agriculture (USDA) in 2013 (United States Department of Agriculture, n.d.). The last assumption was put into place so that travel time and distance would not be a factor in the estimates.

The assumption made during this research was to the increase the Factor of Safety from 2.5 to 3. This was done because of the lack of specific soil information in the Greater Fairbanks Soil Survey. The general classification of soils may not have all the same characteristics of Jarvis-Salchaket complex.

The depth of excavation was another assumption. While gathering data about this project, one expert suggested that a building of this size would most likely get excavated or piled down 30 feet. Since the expert dealt with the DoD and these soil conditions on a continual basis, their insights and recommendations were integrated into the proposed aircraft hangar project.

The research increased the cost by 2.5% if the depth of excavation was greater than 20 feet. This was to factor in the cost of hiring an engineer to design the excavation plan (Northstar Design Solutions, 2017; United States Department of Labor, 2015a). This additional cost is due to OSHA's requirement of having a professional engineer design the excavation site in case of soil failures.

3.1.5 Scaling Cost of Excavation

The United States Department of Labor's (USDL) Occupational Safety and Health Administration (OSHA) has strict requirements when it comes to sloping or shoring excavation sites. An excavation depth of 5+ ft is when contractors are legally required to slope or shore the trench (United States Department of Labor, 2015c). This is to protect workers from potential fatal accidents involving trench failure (United States Department of Labor, 2015a). Sloping, or benching, is the creation of a large V-shaped excavation site expanding outwards as an open pit (United States Department of Labor, 2015a). Shoring is a trench support system where sloping is not possible due to the construction site's area constraints (United States Department of Labor, 2015a). Both types are viable in the discontinuous permafrost regions of Alaska, but Eielson AFB, the researcher's center for this proposed project, has large swathes of land able to accommodate sloping.

According to OSHA, any excavation deeper than 20 ft is required to be designed by a professional engineer (United States Department of Labor, 2015b). This was factored into the analysis for depths greater than 20 ft. Per OSHA's definitions, Type A soils are cohesive soils with a clay composition (United States Department of Labor, 2015a). Type B soils are made composed of angular gravel and some silts (United States Department of Labor, 2015a). Type C soils contain large granular soils or a variant of sand (United States Department of Labor, 2015a). Type C soil was used per OSHA's guide. This is due to the most common soil found on Eielson AFB – Jarvis-Salchaket complex. OSHA specifies a maximum allowable slope of 1.5:1 (H:V) for the researcher's excavation site. This will extend the entire excavation site by 90 ft, 45 ft per side, starting at the slope's edge.

The cost associated with this type of excavation is more time, materials, and equipment (TME). After excavating more than 20 ft, the price will also increase for the time, design, and management of a professional engineer. An additional 2.5% cost was added to the model. This showed an increase in price and overhead for the engineer (Northstar Design Solutions, 2017).

3.2 Data Collection

The most cost-effective foundation method in Alaska must consider three parts. The first being the amount of permafrost located on the proposed construction site, selected by military engineers. The second part is to consider the depth of the excavation. This is to combat frost heave and differential settlement. The third consideration is the occupational use of the structure. The size and maximum loading of the construction requires different foundation types to best fit the needs of all parties involved. All three applications have subsections that would need to be examined closer depending on future studies. This research focused on the occupational use and the amount of permafrost located at the proposed site.

3.2.2 How the Data was Collected

Data is scarce in Alaska since the number of contractors, design agencies, and licensed engineers are limited. However, a total of 15 experts were contacted, via telephone calls, and asked to provide in-house estimates on excavation pertaining to size, location, and if soil replacement was recommended on the fictitious aircraft hangar project. They were also asked if concrete piles, helical piles, and thermosyphons are viable options along with their respective costs. Most of the data sets came from the local vendors and professionals in the field of construction. The local experts' portfolios will include a number of projects pertaining to the DoD or local government buildings. Most of the DoD locations are within the discontinuous permafrost region. Excavation of localized soils were organized by the amount of initial permafrost present and size of the excavation required for this particular project. During our conversations on pricing, most of the engineers and construction managers offered additional knowledge about typical experiences surrounding Fairbanks.

3.2.3 Organizing the Data

A majority of the experts allowed the researcher to use their in-house estimates for cost comparison across the region. The simple unit conversions were used to allow the researcher to compare pricing. Most companies had estimates with ranges using a common construction factor for soils and concrete – cubic yards. There was a total of seven responses from experts that had enough information and data to compare piles and total soil replacement across all criteria set forth in this research. The data that was collected can be found in

.

Table 5. Raw Data Price Ranges

Expert	Qualifying Services	Cost of Excavation	Cost of Permafrost Excavation	Cost of Fill Material	Cost of Concrete Piles
Expert 1	Excavation and Concrete work	$3.00-4.00/CY	$12.00-16.00/CY	$10.00/CY	wouldn't recommend piles unless its majority permafrost (90+%)
Expert 2	Engineering Firm				$120.00/CY of Raw Material
Expert 3	Engineering Firm				$12,000.00/pile
Expert 4	Excavation	$4.00-6.00/CY		$8.00-12.00/CY	
Expert 5	Excavation	$3.50/CY	2-3x $3.50/CY	$25.00/CY	
Expert 6	Construction Management				$8,000.00/pile
Expert 7	Excavation	$3.00/CY	$8.00/CY (2.5*regular price)	$8.00/CY	

Table 6 shows useable cost estimates for their respective fields. Table 6 has all the data simplified to comparable quantities. This was utilized in the analysis portion of this research. The data in Table 6 used the largest estimate given by experts. This is based on a worst-case scenario of having to pay a premium for the services.

Table 6. Highest Cost per Service and Expert

Expert	**Cost of Excavation**	**Cost of Permafrost Excavation**	**Cost of Fill Material**	**Cost of Concrete Piles**	**Cost of Helical Piles**
Expert 1	$4.00/CY	$16.00/CY	$10.00/CY		
Expert 2				$13.083.33/pile	
Expert 3				$12,000.00/pile	
Expert 4	$6.00/CY		$12.00/CY		
Expert 5	$3.50/CY	$10.50/CY	$25.00/CY		
Expert 6				$8,000.00/pile	
Expert 7	$3.00/CY	$8.00/CY	$8.00/CY		

3.2.4 Creating Useful Data for Bases in Alaska

Using all the data that was received, the research created a family of curves for foundation costs in the discontinuous permafrost regions. This will allow military engineers to quickly calculate the cost of the two most prevalent foundation types in the discontinuous permafrost regions – excavation and concrete piles. The independent variable is the depth of excavation or piles; the dependent variable will be the cost. The graph will be linear in nature with changes in slope at 5 and 20 feet. This accounts for the increase in OSHA's excavation safety standards and required professional engineering design.

The graph was split into two main sections: soil excavation and permafrost excavation. The area in-between these two extremes were the amount of permafrost in the soil by percentage. There will also be linear costs representing 60, 40, 30, 20 and 10-

pile costs. The space between each pile threshold will allow users to make judgement calls on the number of piles between 0 and 60.

IV. Analysis and Results

The pricing that was given by the experts are the basis for this research. The cost of the construction market can fluctuate, but the market has held steady for the past five years. This chapter will create a unique tool to provide cost estimate data for the region.

4.1 Results

At first glance, the data in Table 7 seemed to be uniform due to the size and intended purpose of the project. In Alaska, the construction window is limited by the weather. Luck and contractor productivity plays a large role in completing a project on time. The construction window is from May to September between the ground thawing for the summer and when it starts to freeze for the winter. Outside that window, the weather is too harsh for workers and the transition to active layer freezing takes effect. If construction must continue through the winter months, lower productivity results and the cost of excavation dramatically increases. For simplification, the data used in this research are to be used in Alaska's normal construction window, with a normal construction market.

The results shown in Table 7 are the bulk estimates for excavation and subsequent operations in order to fulfill the project's intended purpose. These prices are the basis for creating Figure **11** and Figure **12** that can help military engineers construct a simplified foundation cost estimate pertaining to the discontinuous permafrost region of Alaska.

Table 7. Simplified Cost of Different Construction Methods

Avg CY Excavation Cost (w/o PF)	Avg CY Excavation Cost (w/ PF)	Avg CY Cost Fill Material	Avg Cost per Concrete Piles
$4.13	*$11.50*	*$13.75*	*$11,027.78*
Total Cost of Project Excavation (w/o PF)	**Total Cost of Project Excavation (w/ PF)**	**Total Cost of Project Fill Material**	**Total Cost of Project on Piles**
$183,333.33	*$511,111.11*	*$611,111.11*	*$996,027.20*
0% Permafrost	**100% Permafrost**		
$794,444.44	*$1,122,222.22*		

4.1.2 Visual Graphic

The **Error! Reference source not found.**-12 highlight the cheapest way to construct a stable foundation for the proposed project. The data does not contain thermosyphons or helical piles, since experts agreed that the use of those system are not cost-efficient for the discontinuous permafrost region – specifically, the interior portion of Alaska. The Fairbanks area has some of the cheapest concrete in the state (Butcher et al., 2016). Discontinuous permafrost stability has less capacity to reach the melting point compared to the majority of permafrost located in the continuous permafrost region due to the huge temperature difference.

The first graph, Figure **11**, shows the overall family of curves chart between the depths of 1 and 30 feet. Based on the calculations in Appendix D, 36 piles are needed to safely stabilize the building. Looking at the graph, excavation is significantly cheaper if a shallow foundation is required (less than 10 ft in depth). Though most engineers in the Fairbanks area agree that excavating a site is cheaper, Figure **11** suggests that a low number of piles might be more cost-effective. However, short bored piles typically range from 6.56-13.12 ft (2-4m) in length ("Short bored pile foundation," 2010). Anything at or below 13 ft requires engineering judgement when deciding between excavation and piles. Geological surveying of the site will aid in the decision-making process.

Figure **12** shows the initial price hike after excavation past a depth of 5 ft. This is caused by OSHA trenching requirements to prevent injuries or death due to soil failures (United States Department of Labor, 2015c).

Figure **13**, the secondary price hike, shows the cost for depths between 18-22 ft, due to the additional need for a professional engineer to design a safe trench. This is where all the factors come into play, including the addition of the professional engineering costs and Time, Material, and Equipment (TME) of creating a sloped trench. Thirty-six piles become more cost-effective than excavating with no permafrost. At this depth it becomes an issue of TME and a professionally engineered trench design.

At a depth of 20 ft, a 200'x200' excavation site would become 260'x260'. This is caused by OSHA's standards stating that the minimum slope shall be 1.5:1 (H:V) (United States Department of Labor, 2015a). Type C soil is a loose gravel, sand, or sandy loam; the research chose to be conservative and use the most unreliable soil type for trenching.

Even up to 18-19 ft, excavation is still cheaper than the calculated 36 piles. It does not change until crossing the 20-foot threshold where an engineer must design the trench. Per the family of curves, the calculated 36-pile foundation becomes a contender for a viable, cost-effective foundation type.

The only time piles are more advantageous to excavation is when the amount of permafrost reaches around 25% at a depth of 13-14 ft; the same depth as the transition to short-bored piles becomes useful. Short-bored piles are typically seen between 3-5 meters (12-15 feet) and depends on soil type and structural loading ("Short bored pile foundation," 2010).

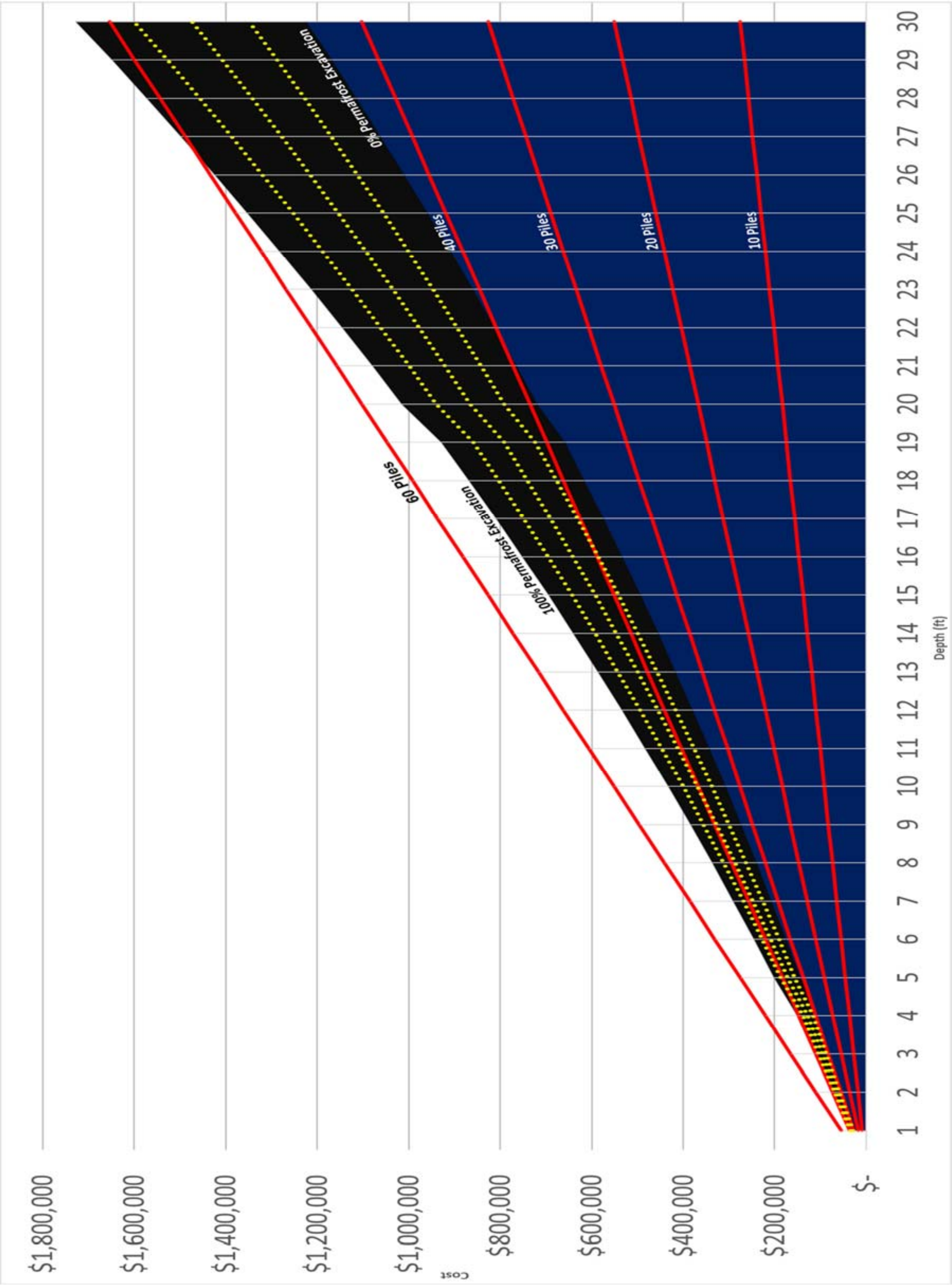


Figure 11. Family of Curves Cost Chart for Depths 1-30 ft

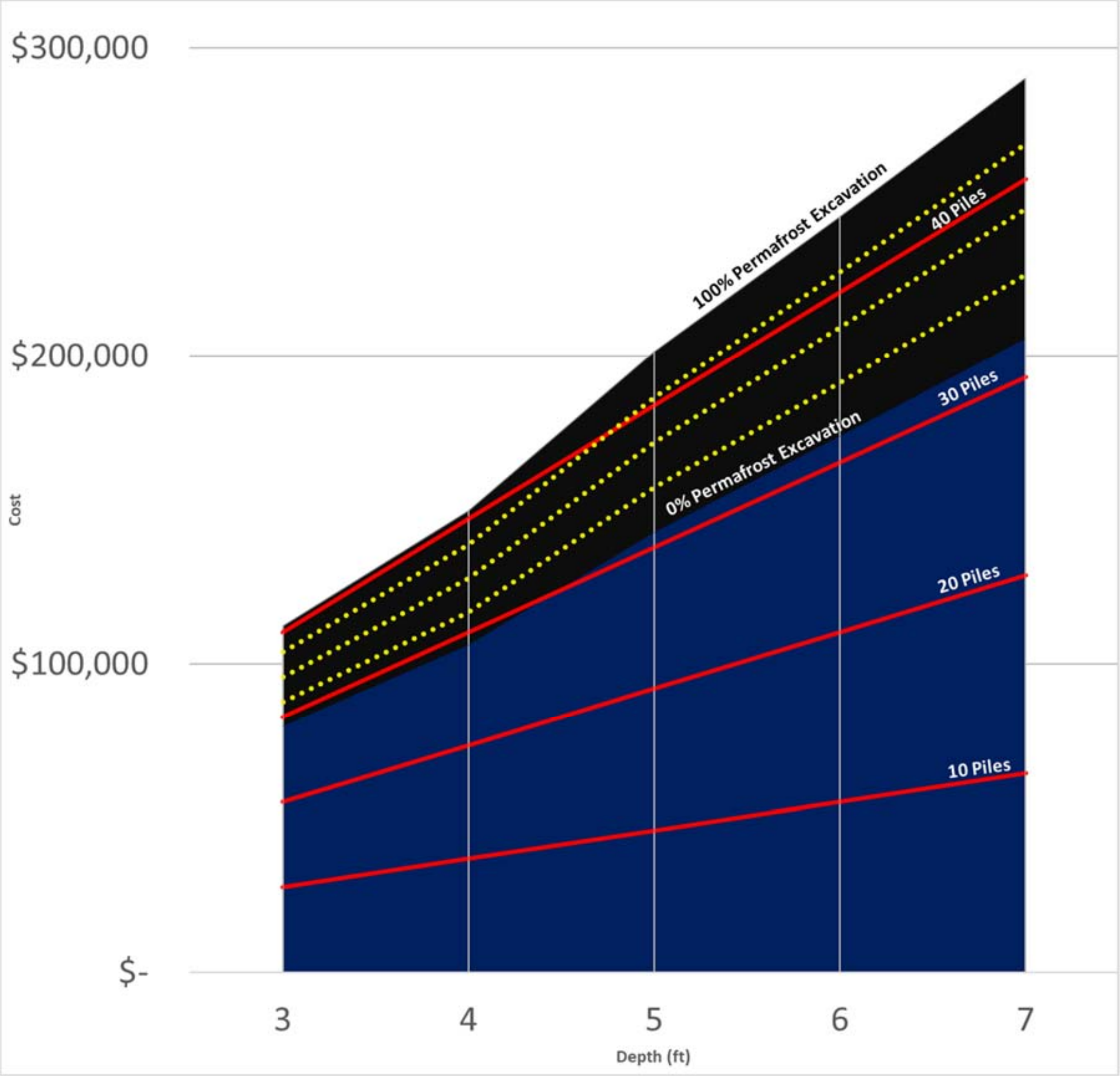


Figure 12. Piles and Excavation Cost Chart, Detailed 5-Foot Increment

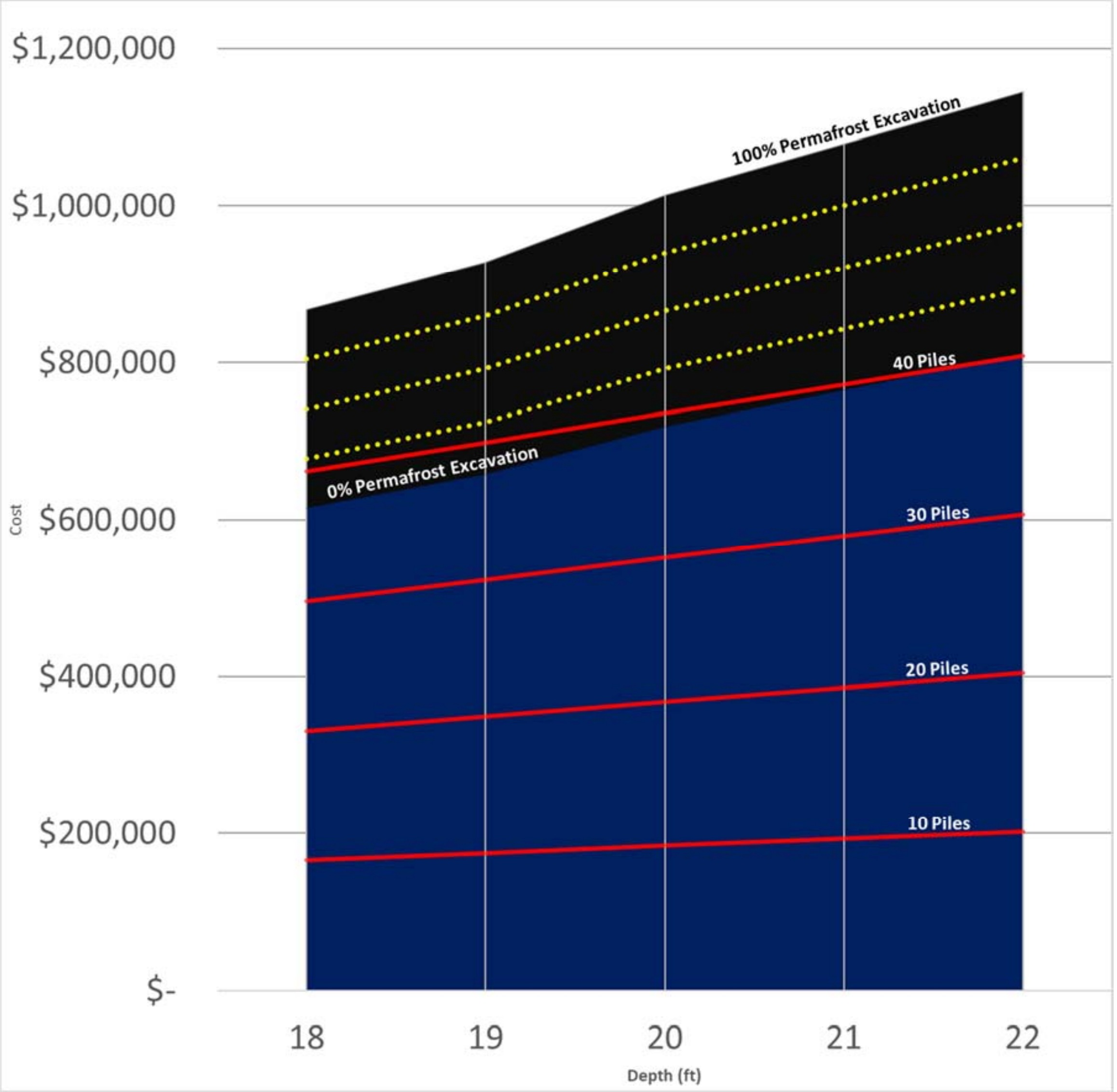


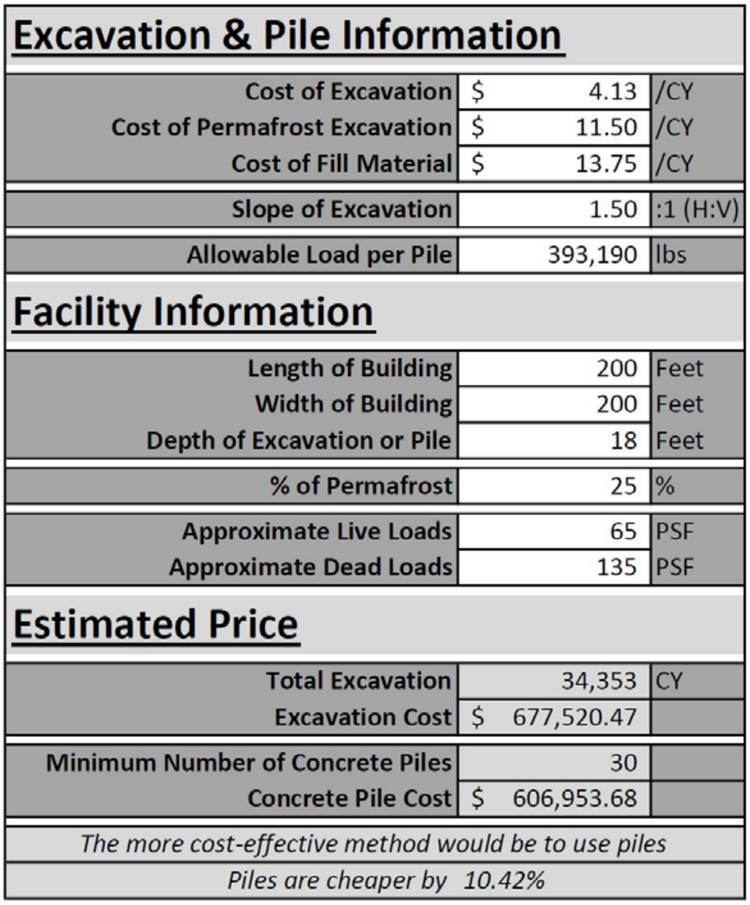
Figure 13. Piles and Excavation Cost Chart, Detailed 20-Foot Increment

4.2 Extrapolating to Other Facilities

The figures mentioned above are specific to a large aircraft hangar but do not translate over to other types facilities. **Error! Reference source not found.** is a screenshot of the calculator developed by the researcher. It will allow users to change the cost of cut and fill under the "Excavation & Pile Information" section. The user can update estimated pricing to match future trends. This section of the calculator also includes areas to adjust the slope of excavation and the allowable pile loading. The slope of excavation will allow the user to change the slope depending on the type of soil at the construction site. The allowable piling loading was based on the calculations in Section 3.1.4. The user can now adjust the pile load based on different pile criteria.

"Facility Information" includes the rudimentary basics for understanding the scope of the facility. The user can input general requirements and approximate loading. The last section, "Estimated Price," will let the user see the difference in pricing between piles and excavation. It will also tell them the delta between the types of foundations.

All the characteristics that were built into the calculator were based on the data gathered by experts and the researcher's soil assumptions. This calculator will give users in Alaska a deeper understanding of cost estimating in the discontinuous permafrost region. Estimates might fluctuate due to inflation, contractor competition, inconsistent weather, or location. This will help bases itemize costs and decrease the chances of underestimating future projects. In turn, bases may experience less frequent congressional reapprovals if pricing and estimates are more accurately represented the first time.



Excavation & Pile Information		
Cost of Excavation	$ 4.13	/CY
Cost of Permafrost Excavation	$ 11.50	/CY
Cost of Fill Material	$ 13.75	/CY
Slope of Excavation	1.50	:1 (H:V)
Allowable Load per Pile	393,190	lbs
Facility Information		
Length of Building	200	Feet
Width of Building	200	Feet
Depth of Excavation or Pile	18	Feet
% of Permafrost	25	%
Approximate Live Loads	65	PSF
Approximate Dead Loads	135	PSF
Estimated Price		
Total Excavation	34,353	CY
Excavation Cost	$ 677,520.47	
Minimum Number of Concrete Piles	30	
Concrete Pile Cost	$ 606,953.68	
The more cost-effective method would be to use piles		
Piles are cheaper by 10.42%		

Figure 14. Foundation Estimate Calculator

4.3 Calculator Verification

To verify that the calculator's estimating process is correct, Eielson AFB's F-35A complex was the test project for the calculator. The project is titled, F-35A Hangar/Propulsion MX/Dispatch Facility, and the information has been dated 17 February, 2017. Figure **15** is a rendering of what the facility will look like at completion. This project is a mixture of a smaller aircraft hangar with office and maintenance space at the same location. The size of the facility is slightly smaller at 33,928 square feet

(Coffman Engineers, 2017). The information being presented is prior to construction and will not reflect any abnormal weather delays or unknown site conditions.

Figure 15. F-35A Facility Rendering

Reviewing the project's geological and civil design analyses, the researcher can infer some of the soil conditions. From the civil design analysis, it appears as though the site has shallow layers of permafrost that may continue to a depth of 70 feet (Civil Design Analysis, 2017; R&M Consultants, 2017). The reports did not specify an amount, so the researcher assumed the site contains approximately 18% permafrost. They described the site as having the potential for "excessive long-term differential settlement" (R&M Consultants, 2017). A total of 46 boreholes were tested throughout the site, ranging from 15.2 feet to 100 feet (Golder Associates, 2017). Some of the soils found on site were silty sands, sandy silts, and poorly-graded gravel; there were more soils and all were described as “frozen” or “wet” (Golder Associates, 2017). The researcher assumed a different soil, but precautions were taken to account for water content and compaction. The average groundwater table was identified at a depth around 5 feet, similar to the assumptions made in the researcher’s project (Civil Design Analysis, 2017).

The drawings indicate that the depth of excavation will reach 8-14 feet below the surface (US Army Corps of Engineers, 2017). The calculator assumed an average depth of 14 feet for the verification process. OSHA trenching requirements were mentioned clearly at the start of most of the documents. Sloping the site must have a minimum of 1.5:1 (H:V) (Civil Design Analysis, 2017, Structural Design Analysis, 2017). The researcher’s calculator kept the same slope as mentioned in the reports.

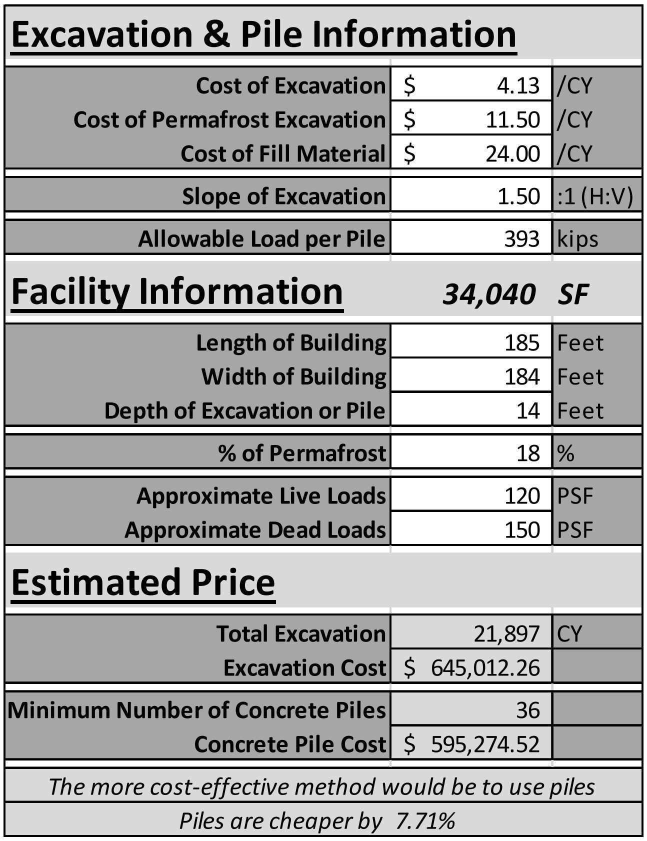
Live loads were calculated by room and occupancy type. They ranged from 40 PSF for catwalks to 200 PSF for aircraft storage area (Structural Design Analysis, 2017). An average of 120 PSF will be used for the calculator. Dead loads were calculated according to ASCE 7. A combination of office space, corridors, storage areas, and aircraft maintenance area materials were used in the design of the dead loads (Structural Design Analysis, 2017). For the calculator, dead load was increased from 135 PSF for the researcher’s project to 150 PSF for the verification.

Figure **16** shows the estimated price based on the information extracted from Eielson AFB’s F-35A project. The calculator estimated the excavation would be the more cost-efficient method by 7.71%, and the cost of excavation is $645,012.26. The

DoD paid the contractor $701,282.00 to excavate the site, a difference of 8.73% from the researcher's calculator - excluding two discrepancies.

The bid had earthwork for a total price of $5,120,137, A vast difference from the researcher's estimated cost (U.S. Army Corps of Engineers, 2017). There was a huge discrepancy for the cost of fill material. The government paid almost double for fill material, $13.75 compared to $24.00 (U.S. Army Corps of Engineers, 2017). This was adjustable in the calculator, but the sub and prime contractor costs increased the total fill material to $2,137,482 (U.S. Army Corps of Engineers, 2017). Of that total cost, $788,059 was dedicated for contractor cost and contingency cost, both were not addressed in the researcher's calculator (U.S. Army Corps of Engineers, 2017).

The second discrepancy is that the contractor cites a "steam thawing" process for the entire excavation site - a service that the government paid $2,281,371 (U.S. Army Corps of Engineers, 2017). No description was included in this line item as to why this was done. The researcher assumed the site was majority permafrost and did not reflect that in the calculator or in the soil samples done by a contractor. Even if the researcher increased the percentage of permafrost to 70-80%, it would not reflect the F-35A project total earthwork cost.



Excavation & Pile Information		
Cost of Excavation	$ 4.13	/CY
Cost of Permafrost Excavation	$ 11.50	/CY
Cost of Fill Material	$ 24.00	/CY
Slope of Excavation	1.50	:1 (H:V)
Allowable Load per Pile	393	kips
Facility Information	***34,040***	***SF***
Length of Building	185	Feet
Width of Building	184	Feet
Depth of Excavation or Pile	14	Feet
% of Permafrost	18	%
Approximate Live Loads	120	PSF
Approximate Dead Loads	150	PSF
Estimated Price		
Total Excavation	21,897	CY
Excavation Cost	$ 645,012.26	
Minimum Number of Concrete Piles	36	
Concrete Pile Cost	$ 595,274.52	
The more cost-effective method would be to use piles		
Piles are cheaper by 7.71%		

Figure 16. Calculator Verification

4.4 Analysis

The analysis section compared construction costs with Alaska's closest competitor – Washington State. It will also discuss the reasons why helical piles and thermosyphons were not used in the discontinuous permafrost region.

4.4.1 Comparing Data to Washington State

Washington is Alaska's closest construction competitor as described by the surveys done by Alaska's Department of Labor (Butcher et al., 2016). In Seattle, the cost of excavation is $3.40 per cubic yard, which is 19% cheaper than the expert quotes received from Alaska (Building Journal, 2017). If permafrost was a construction factor in Seattle, an increase of 338% to their typical excavation cost could be expected. This proves that permafrost is a major factor when locating a site for construction. In 2014, the U.S. average price for concrete was $98 per cubic yard (Concrete Network, 2017), which is 23% cheaper than the average concrete cost of $120.40 per cubic yard in Fairbanks. Overall, Alaska has increased pricing due to the remote location of most major Alaskan cities.

4.4.2 Discussing Helical Piles and Thermosyphons

Helical or screw piles were not considered by local experts because of the inconsistent nature of permafrost in the specified region. Helical piles are more effective in sandy and granular soils because of potential vertical loads applied on each pile (Al-Baghdadi, Brown, Knappett, & Al-Defae, 2017; Malik, Kuwano, Tachibana, & Maejima, 2017). This type of system, when used in permafrost, is mostly used when permafrost cannot or should not be removed. This type of construction can be found on the northern coast of Alaska or any other region within the Arctic Circle (Wang, Liu, Zhao, Shang, & Liu, 2016). The temperature of permafrost is a major factor affecting how construction should take place. Since the continuous permafrost region has a lower annual temperature, the permafrost found in the region is more stable and abundant than those found in the discontinuous permafrost region (Batir, Hornbach, & Blackwell, 2017).

Thermosyphons was the other system that was not quoted during this research. Thermosyphons were said to be only typically used for extreme cases that permafrost dictates the environment and surrounding area. The distinct use of thermosyphons is to maintain equilibrium of the permafrost (Feoktistov, Vympin, & Nurpeiis, 2016). Equilibrium can only be achieved when annual temperature is well below freezing – more common in the continuous permafrost region (Hernández, Bautista, & Ortiz, 2016). The majority of the land in the discontinuous permafrost region is not permafrost. Experts argued that moving the construction site a couple of feet in any direction drastically changes the amount of permafrost under the facility. Because of that knowledge, if there was enough permafrost to warrant more than excavation, piles would be the secondary option.

V. Conclusions and Recommendations

The outcome of this research points to the conclusion that there are only two main foundation methods used in Alaska's discontinuous permafrost region – excavating the site and concrete pile foundations. Other types of pile foundations are not as cost-effective as concrete piles since concrete in Fairbanks is the second cheapest in the state, about $112 per cubic yard (Butcher et al., 2016). Excavating is the cheapest method per cubic yard. Another advantage of excavation is that it removes any of the unknowns in the soil. The USDA soil survey indicates that there are large amounts of soil capable of harboring permafrost and having properties that produce settlement, like high water tables and unsatisfactory drainage. This, compounded with large frost heaving in the active layer, can be catastrophic for a building. Replacing the soil with a trustworthy fill material can prevent future settlement and drainage issues that plague under-designed buildings in Alaska. Thermosyphons and helical piles are designed for more extreme scenarios. For example, thermosyphons are used on the Trans Alaskan Pipeline because the temperature of the oil can reach up to 140° F (Maxim, 2001). As for helical piles, they work better in large sheets of permafrost where they can be anchored into the frozen soil.

Dependent on the depth of the pile or excavation, the soil type, amount of permafrost, and type of facility, the cost estimate calculator created during this research can aid military engineers with their estimate for their construction projects.

5.1 Impact of Military Construction

For the bases located in the discontinuous permafrost regions of Alaska, new construction will be a prominent part of military civil engineer units. This research has shown that the amount of permafrost has a direct effect on cost. Permafrost is a major factor in settlement issues. Because military equipment has very low tolerances, addressing settlement issues with proper planning and design of a facility is critical. The calculator developed by the research will be a tool utilized by engineers to reinforce estimates and execution methods. Both can be reduced drastically through accurate geotechnical reports and adequate backfill.

5.2 PACAF's Future Construction

The future of construction is pointing to more discontinuous permafrost due to climate change – the shrinkage of landmass covered by continuous permafrost. PACAF will need to continue to invest in geotechnical reports to better suit the needs of the facility, but in the future, geotechnical reports will not be used to detect large amounts of permafrost. The reports will be used to determine how much backfill is required to build a solid foundation. Incoming flying missions will not have a problem with permafrost due to the developed area surrounding the runway. Other missions will have land on the outskirts of bases where permafrost may be more abundant than the interior of the base.

5.3 Significance of Research

This research identified the two most common foundations used in Alaska's discontinuous permafrost region. With this insight, cost estimates supported by this calculator and practical information, military engineers can now build reliable estimates for future construction projects. Building a solid cost estimate will allow PACAF to control their budget. Creating a 5- or 10-year construction plan with sound cost estimates will alleviate stresses of acquiring Congressional reapproval for projects. This in turn will allow bases to plan critical missions more effectively and operate at steady state.

5.4 Recommendations

Vital military operations will have a large impact on where new construction of facilities occur. Since permafrost will not dictate the relocation of major facilities due to mission requirements, engineers will have to depend on data gathered from the potential site. Geological surveys and design analyses can greatly reduce unknowns for a site. Analyzing the site, coupled with the researcher's calculator, will help engineers convey pertinent information regarding the future of a project.

5.4.2 Utilizing Geotechnical Reports

Especially in discontinuous permafrost region, geotechnical reports determine the probable amount of permafrost and soil composition. This will help determine which foundation to use and how much excavation will be required for a project. These items are expensive in Alaska and should be accurate enough to budget future projects that PACAF needs to maintain its presence in the region. Since soil is not consistent over large areas, Eielson AFB will benefit greatly from geotechnical reports since the base is sprawling with large unused areas to the East. Fort Wainwright is located more in town where land becomes a valuable commodity. This army installation will still benefit from geotechnical reports by way of determining the soil composition and planning accordingly due to Fairbank's high silty, clay soil.

5.4 Future Research

The results of this specific research have shown that the high cost of excavation coupled with the type of soil native to the Fairbanks area lends itself more to soil replacement than any other type of large-scale foundation. Future research in this area could include:

1. A historical look at foundation or construction costs at Eielson AFB to identify the amount of spending per CSI.
2. Create a calculator for earthwork construction costs in the continuous permafrost region where thermosyphons, helical piles, and other extreme weather foundations are more relevant.
3. Eielson AFB spends a large portion of their construction budget for soil remediation since their soil is contaminated. A closer look into the situation and how to mitigate the cost may be effective for saving the Air Force construction funds for other requirements around the world.

These future research topics would help Alaskan military installations combat permafrost. Climate change and the effects it has on permafrost may be another ideal research topic if others wanted to branch out of the construction side of the permafrost question.

Appendix A. Soil Survey Map of Eielson AFB

Figure 17. Eielson AFB 2015 Soil Survey Map (United States Department of Agriculture, 2017)

Appendix B. Soil Survey Map of Fort Wainwright

Figure 18. Fort Wainwright 2015 Soil Survey Map (United States Department of Agriculture, 2017)

Appendix C. Excavation and Pile Calculations

Total amount of soil excavation required for the fictitious project:

$$\boldsymbol{Total\ Excavation}\ (\boldsymbol{CY}) = \frac{(Length * Width * Depth)}{Cubic\ Feet\ to\ Cubic\ Yards\ Factor} =$$

$$= \frac{(200ft * 200ft * 30ft)}{27\ {ft^3}/{CY}} = \mathbf{44,444.44}\ \boldsymbol{CY}$$

$$\underline{\boldsymbol{Total\ Excavation}\qquad = \mathbf{44,444.44}\ \boldsymbol{CY}}$$

The total cubic yards of concrete needed for each 30 ft pile:

$$\textbf{Total Concrete Required per Pile (CY)} = \frac{\pi * \frac{Diameter^2}{2} * Depth}{Cubic\ Feet\ to\ Cubic\ Yard\ Factor} =$$

$$= \frac{\pi * \frac{2.5\ ft^2}{2} * 30\ ft}{27\ {ft^3}/{CY}} =$$

<u>Total Concrete Required per Pile (CY) = 5.45 CY/pile</u>

Appendix D. Cost Calculations

$$\boldsymbol{Cost\ of\ Project\ Excavation\ (w/o\ PF) = Avg\ Excavation\ Cost\ (w/o\ PF) * Total\ Excavation}$$

$$= \frac{\$4.13}{CY} * 44{,}444.44\ CY = \$\mathbf{183,333.33}$$

$$\textbf{Cost of Project Excavation (w/ PF)} = \boldsymbol{Avg\ Excavation\ Cost\ (w/\ PF) * Total\ Excavation}$$

$$= \frac{\$11.50}{CY} * 44{,}444.44\ CY = \$\mathbf{511,111.11}$$

$$\textbf{Cost of Project Fill Material} = \boldsymbol{Avg\ Fill\ Material * Total\ Excavation}$$

$$= \frac{\$13.75}{CY} * 44{,}444.44\ CY = \$\mathbf{611,111.11}$$

$$\textbf{Cost of Piles} = \boldsymbol{Avg\ of\ Concrete\ Piles * Total\ Number\ of\ Piles * ACF}$$

$$= \frac{\$11{,}027.78}{Pile} * 36\ Piles * 2.51 = \$\mathbf{996,027.20}$$

$$\mathbf{0\%}\ \boldsymbol{Permafrost} = \textbf{Cost of Project Excavation } \boldsymbol{(w/o\ PF)}\ +\ \textbf{Cost of Project Fill Material}$$

$$= \$183{,}333.33 + \$611{,}111.11 = \$\mathbf{794,444.44}$$

$$\mathbf{100\%}\ \boldsymbol{Permafrost} = \textbf{Cost of Project Excavation } \boldsymbol{(w/\ PF)}\ +\ \textbf{Cost of Project Fill Material}$$

$$= \$511{,}111.11 + \$611{,}111.11 = \$\mathbf{1,122,222.22}$$

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14. ABSTRACT

This research uses a quantitative analysis to develop a family of curves and a calculator for potential foundation thresholds in the discontinuous permafrost region of Alaska. The United States Pacific Command (PACAF) is bolstering the region by advocating for the F-35, KC-46, and the newly proposed long-range bomber to be stationed in Alaska. These next generation aircrafts and warfighters will need new facilities and beddown plans to efficiently and effectively carry out their mission. The biggest obstacle in the region is permafrost; this unique polar phenomenon is found throughout the northern half of Alaska. Fairbanks in particular has multiple military bases that could benefit from knowing which foundation type would excel in the region. With the help of seven experts in construction, excavation, and geotechnical engineering fields, the researcher discussed methods of constructing a fictitious foundation located at Eielson AFB. The average regional cost per cubic yard of soil is \$4.13; however, the average cost to excavate permafrost catapults to \$11.50. With different types of proven foundations used in Alaska, all experts agreed that helical piles and thermosyphons are for extreme scenarios and would not be cost-effective in the discontinuous permafrost region. Concrete piles and excavation being the two true contenders for the area, the researcher discovered that excavating is superior to concrete piles until the volume of permafrost exceeds 94% of the construction site. Even though Fairbanks has one of the cheapest concrete batch plants in Alaska, excavating and hauling fill materials miles away is ultimately cheaper for the military.

15. SUBJECT TERMS

Alaska, construction, foundation, permafrost, excavation, pile

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