International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 4 Issue 10 ǁ October. 2016 ǁ PP.59-71

A Review on Permafrost Geotechnics, Foundation Design And New Trends

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Abstract: Soil mechanics and geotechnical engineering that are used in mild climates are based on soil temperatures above freezing point. When the temperature falls below freezing point, seasonally or during the whole year, permafrost geotehnics application becomes necessary. Water phase change from liquid to solid mutually induces frost heave and frost thaw as the main geotechnical problems in frozen soils. Permafrost covers vast area of planet Earth, and therefore many types of structures are built in the permafrost conditions. In this paper a comprehensive review on geotechnical problems and solutions for different types of civil structures in permafrost has been performed. Structures that are discussed include shallow and deep foundations, thermosyphones, roadways, railroads, bridges, and pipeline foundation. It was concluded that special geotechnical engineering for permafrost projects is necessary to avoid main problems. Historical and new projects are approval for existence of these geotechnical problems and necessity of mitigation methods for future projects. Depending on type of project, active or passive cooling systems and thaw resistant techniques or combination of all should be applied to build a stable structure in the permafrost regions.

Keywords: permafrostgeotechnics,thermosyphone, roadway, railway, pipeline foundation

I. INTRODUCTION

Practice of soil mechanics for mild climatesis established on soil temperatures above freezing point. In permafrost regions, heat transfer as a main factor impacts freezing and thawing process in the seasonal frost(Barker *et al.* 2013).Change of phase in soil water content from liquid to ice, and vice versa has significant effect in physical properties of the soil. These properties are very sensitive to variation in soil temperature. Considerable heaving by pore-water migration in freezing happens in addition to in-situ heaving phase change, from water to ice (Barker *et al.* 2013).

Climates with temperature 0°C or below in the coldest month of the year is used to determine southern border of frost in the cold regions of North America. Depth of seasonal frost incursion equal to 30 cm or more below ground level, one time in every 10 years is considered a norm for detection of this boundary(Barker *et al.* 2013). The cold regions are classified into two types. A type, where the ground is frozen in a season only, and other type lasts all year around.Also in other classification, the permafrost exist everywhere (continuous), or permafrost exists just in some places (discontinuous). Usually, the mean annual ground surface temperature should be lower than -2.7° C for maintaining permafrost condition(Barker *et al.* 2013). In non-permafrost regions, depth of seasonal frost is defined as the maximum depth of freezing duringthe season. In permafrost regions that frost lasts during whole year, active layer is defined as the maximum depth of thaw and, beneath that, the ground remains frozen all over the year(Barker *et al.* 2013). Frost susceptible soils, controlled by capillary rise and permeability, usually heave when enough water in the soil exists and expands due to the ice formation. Generally, soils with more than 10 percent fine particles passing the #200 sieve can be assumed as a frost susceptible soils considering following exceptions. In low capillary rise and high permeability conditions similar to gravels, ice segregation happens; therefore heave will not occur. In other end i.e. in clays, capillary rise is very high and permeability very low, so limited volume of water is drawn up into a clayey soil, and limited ice lenses are formed in turn. Despite to the gravels and clays, silts with enough capillary rise and permeability are highly frost-susceptible(Barker *et al.* 2013). The geotechnical characteristics of naturally frozen soils are very important for northern civil engineering projects. The type of sampled frozen soil, the in situ thermal gradient, the time and method of sampling, and transportation impactthe quality of frozen soil samples for tests. Melt of ice lenses formed during frost heave, and pore water expulsion cause settlement. Also, shear strength is lost in the soils which are called “thaw unstable” soils(Barker *et al.* 2013). Permafrost gets impact from climate change, and human activity. They are controlled by variation in active layer thickness and permafrost thermal gradient. Thawing of ground ice close to the permafrost table forms irregular and uneven thaw settlement and thermokarst. These features induce great danger to infrastructures and structures, which are laid on permafrost region (Nelson *et al.* 2002). Usually, the design procedure for foundation in permafrost area is done by protecting permafrost from melt and controlled thaw after building the foundation. By protecting the permafrost from melt, the thaw settlement not only is avoided, high loading capacity of cold permafrost area is applied in design too(Wei *et al.* 2002).

Study of permafrost geotechnics includes different topics. In this paper, a review considering new trends in foundation design especially pile foundation, thermocyphones, road and railway, and pipeline foundationare presented.

II. FOUNDATION DESIGN ON PERMAFROST LANDS

Common foundations if are constructed on frozen soils transfer heat into the frozen ground. The ice inside the soil is melt and structure experiences settlement and structural damage (Fig. 1) if regular foundations are used in frozen soils(Clarke, 2004). Primary design step should include the optimal foundation type considering permafrost ground conditions and the structure standards. This step should suggest foundation design requirements e.g. piles, granular pad with air space, or thermosyphons. Some parameters are required to be obtained that include pile adfreeze strength with design ground temperature, and potential uniform and differential settlement during the structure service life.Adfreeze can be defined as a strong adhesive connection that is produced during the time that soil freezes in contact with foundations, e.g. piles. Positive and negative aspects of selected foundation type along with alternative foundation types should be addressed and reported in design step(Holubec, 2008).

Structurally enhanced foundation (SEF) is more favorable by owners and financial lending institutions to avoid settlement due to permafrost melt. SEF is actually a grade-beam foundation, under which spread footings for pinning may or may not be used. SEF system is usually good to be used where the evaluated total settlement from thaw strain is less than 0.3 m (Clarke, 2004).

Fig. 1 Large differential settlement in a structure in permafrost region, Fairbanks(Modified after Clarke, 2004).

The SEF idea can be simplified by modeling a foundation as a beam system or a cantilever mode by using reinforcing steel in the bottom and top of the SEF footing (Fig. 2). Load disturbance resulted from thaw strain are located under them(Clarke, 2004).

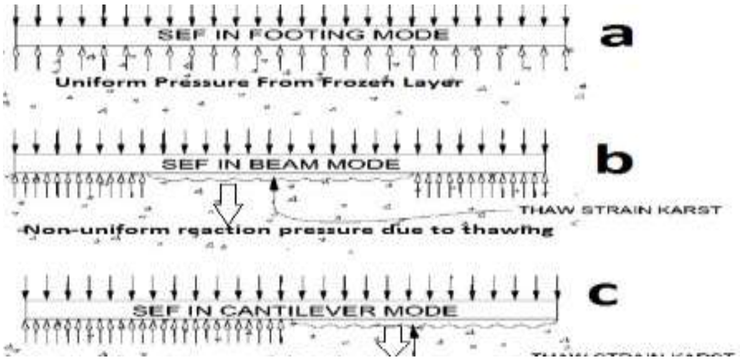

Fig. 2 SEF system in a) Footing mode, b) Beam mode, c) Cantilever mode(Modified after Clarke, 2004).

Pad and post is another permafrost foundation system with lowest price that includes a concrete or wood pad located on the ground or hidden under the ground (Fig. 3). The structure is maintained on a system of rigid beams. These beams avert excessive racking of the structure during settlement or re-leveling. A free air space under the structure is provided by columns that thwarts melting of the frozen soils and can be covered by some ornaments or decoration(Clarke, 2004).

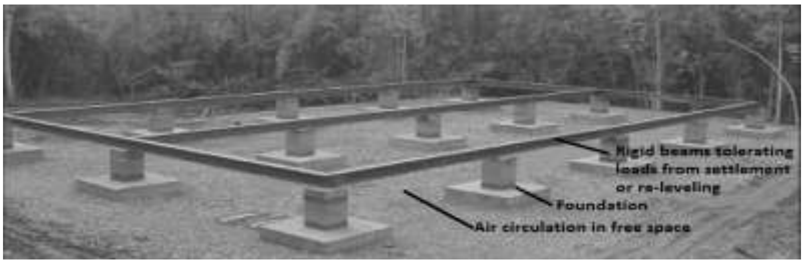

Fig. 3 An example of pad and post system(Modified after Clarke, 2004).

Beside adjustable foundation designs other foundation systems which are common in permafrost areas are slab-on-grade, crawl space, external support, and basement foundation systems(Clarke, 2004). Slab-on-grade foundations are getting popular in Canada, especially in rural, northern and First Nations housing (Fig. 4). This system provides a cost and energy-effective, and durable foundation. Positive aspects of this system can be summarized as: reduction in the potential for soil moisture and pressure problems by building it in a grade level, and reduction in cost of heating air by removing the basement option(CHMC 1998).

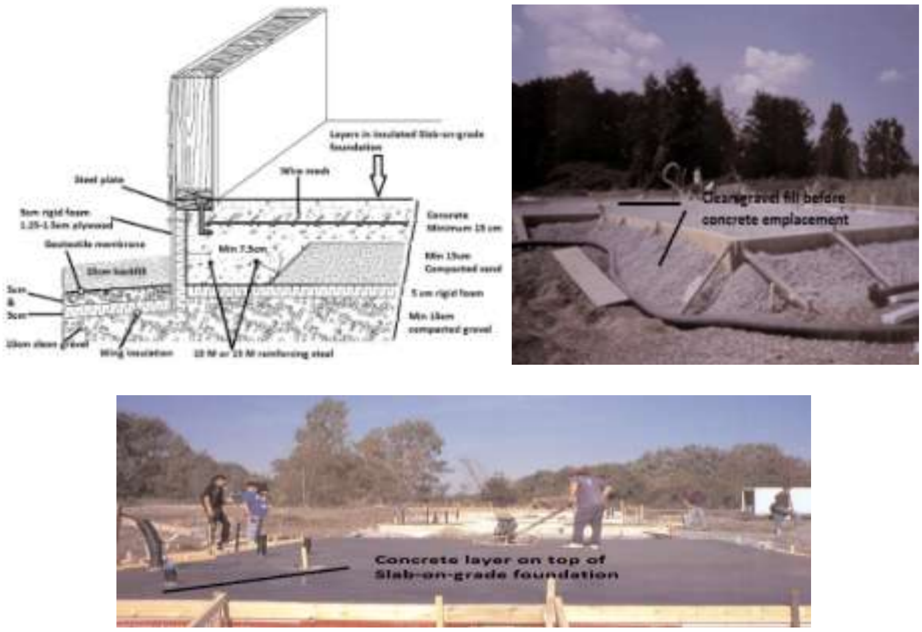

Fig. 4A schematic and a real example of insulated Slab-on-grade foundation(Modified after CHMC 1998).

To avoid or reduce the potential for frost heave and settlement, foundations must be emplaced on an undisturbed soil that does not have any organic matter. A slab that transfers the structure loads to soils underneath is used. Another point is insulation for heat flow, providing desirable heat for occupants inside along with frost protection. Design in permafrost areas should use some methods to retain the ground in frozen status rather than unfrozen. Also, air, soil gases and water leakage into the home should be prevented (CHMC 1998).

One of the refrigerated spread footings applications can be spread footings with a grade beam or post and pad foundations. They are usually less expensive than the slab-on-grade or pile foundations. This refrigerated foundation can employ an insulation layer on the tope of cooling system to decrease heat flow from the ground surface and lower cooling load requisite. Mechanical refrigeration or thermosyphon can be used for refrigeration in this foundation(Clarke, 2004). Refrigerated on-grade foundations are usually employed in sites with heavy floor loads. Examples could be warehouses, garages, reservoir tanks, industrial complex. Components of the foundation usually are concrete slab, a layer of bedding sand, a layer of insulation, a system with piping for refrigerating, and a non-frost susceptible pad over the soil in the site. Usually a membrane is used to prevent the insulation layer degradation by leakage or spill of petroleum or its products(Clarke, 2004). The best design method for this type of foundation is obtaining optimized design and material in foundation using numerical methods. Active systems, and passive systems have been used successfully in permafrost area projects. Active systems were methods that used a vapor-compression (mechanical) refrigeration (in airport buildings of Barrow and Deadhorse, Alaska) and cooled liquid where the liquid was pumped and cooled by ambient air in a fan coil unit (in vehicle maintenance shop at Dalton highway, Alaska). Passive system were equipment such as air ducts (in a fabrication shop of Sohio in the Prudhoe

BayOilfield in Alaska), or thermosyphons (in federal aviation administration in Fairbanks, Alaska)(Clarke, 2004).

2.1 Pile foundation in permafrost areas

Piles, another common foundation type in permafrost areas should tolerate instant loads from structure and long term loads from frost-heave caused by the annual freezing of the active layer. If the frozen soil thaws seasonally, it will settle and cause downdrag load that should be resisted by pile. However predrilled piles have higher bearing capacity than driven piles, the ground temperature is main influent factor in this capacity. End of summer temperature profile for the warmest time is considered for obtaining adfreeze values for the soil, ice andslurry conditions. Also pile type, and predictable creep settlement rate during structure service are a function of ground temperature.Polyethylene films are used in drilled (slurry) piles to break adfreeze bonds (Fig. 5).

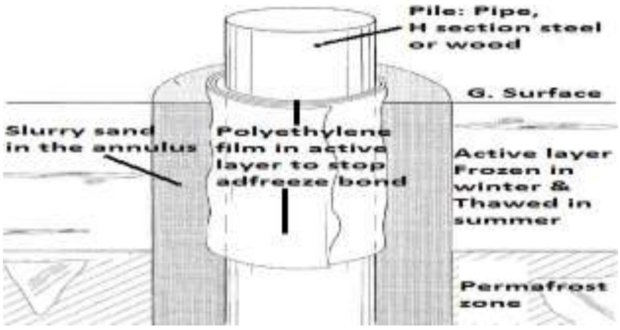

Fig. 5 Slurry pile with Polyethylene film around it (Modified after McFadden, 2004).

Piles in permafrost should be designed in such a way that piles keep the settlement in acceptable range. Meanwhile, applied load should not be more than the short term adfreezestrength of the pile-soil contact(Nixon 1978).

There are different terms which are used for cooling system of piles to prevent thaw in warmer times. Thermal pile, or thermosyphon or thermosiphon, or thermopile or thermoprobe or heat pipe or heat tube or thermotube are used interchangeably to address this foundation system (Clarke, 2004). Design usually take into the account the tangential adfreeze strength at the soil-pile interface, which is maximum stress that creates failure of the adfreeze bond between the pile and the frozen soil.In this method settlement allowance during service life is not considered, however settlement can be limited by applying higher factor of safety. A method for rational consideration of settlement exists. In this method the creep of ice-rich frozen soil is approximated using a constant creep rate during service life(Nixon 1978). Then, the creep law, or flow law, is applied in a mathematical model for the pile, pile-soil contactand the adjacent continuum. Finally settlement rate by applying a known pile load is calculated through a solution.

A research on adfreeze strength of different piles in permafrost conditions using Ottawa sand as the soil material was conducted (Fig. 6)(Parameswaran 1978). It was concluded that the maximum adfreeze bond strength happens in uncoated wood piles (B.C. fir and spruce). However, adfreeze bond strength in concrete piles were lower than wood; it was higher than steel and coated piles. Application of coating material such as creosote, paint, and etc. decreased adfreeze bond strength significantly. From low to higher values of adfreeze bond strength, following piles were sorted in order. From painted steel pipe in the lowest rank, to the creosoted B.C. fir piles, unpainted steel H-sections, cylindrical section, concrete, uncoated spruce, and uncoated B.C. firto higher and the highest value(Parameswaran 1978).

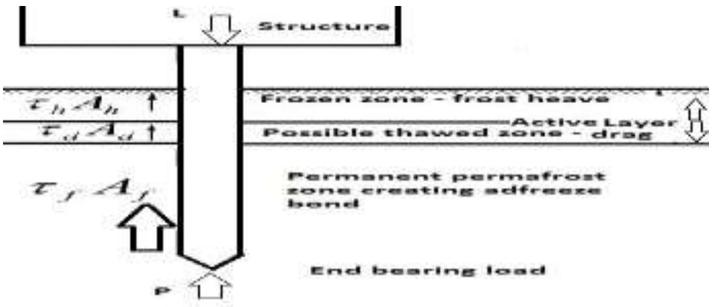

Fig. 6 Depicting different types of forces on a pile foundation in permafrost environment (Modified after Parameswaran 1978).

Gravels and boulders are a porous media with very effective natural convection in winter and only conduction in warm seasons. These material if combined in grooves with specially designed piles (Fig. 7), thawing in the frozen soils can be avoided (Li and Xu, 2008).

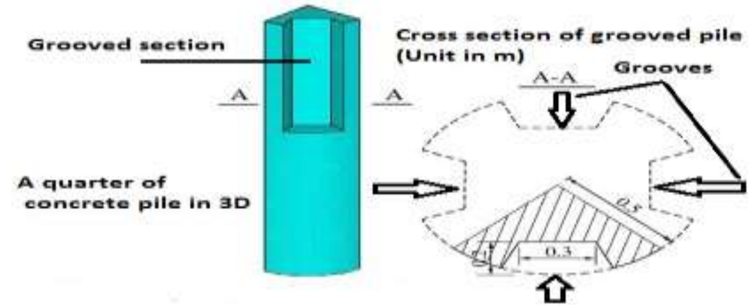

Fig. 7 Special designed concrete pile with grooves(Modified after Li and Xu, 2008).

In winter time, in the grooved concrete pile surrounded with gravel and boulder size grain, cold air moves downwards and chills the adjacent soils. In summer time, lower part with colder air has higher density than warmer air at the top which prevents convection. Heat exchange in conduction mode happens in negligible amount.It was observed that with using the specially grooved pile, the refreezing time for adjacent soil is decreased around 40% in comparison to normal piles(Li and Xu, 2008). Permafrost table will increase because of more cold air penetration and thawing settlement will decrease. In turn, bonding strength will increase leading to 16% increase in bearing capacity in 10 m long pile with 1m diameter comparably. With stable frozen period, the frost heaving force is decreased by 80% (Li and Xu, 2008). In lateral loading of piles, pile fixity near the bottom of the active layer is considered for permafrost soil conditions. Experiments in permafrost showed that laterally loaded piles will typically bend near the top of the frozen surface. They show higher resistance to thelateral loads during short-term loading cases(Nottingham and Christopherson1978).

Also creep settlement rate calculation for piles in saline permafrost using following equation obtained from the non-linear creep law can be obtained (Nixon and Lem 1984;Nixon and Neukirchner 1984).

$$\ddot{u}_a = \frac{3^{(n+1)/2} aB\tau_a^n}{n-1} \qquad (1)$$

Where $\ddot{u}_a$ = Pile displacement rate

a = Pile radius

τ_a = the applied stress on the pile shaft

n = Creep exponent

B = Creep coefficient

Settlement of courthouse building in Alaska using above equation estimated the general rates of creep in piles closely(Miller and Johnson 1990). Sensitivity of obtained rates to small changes in temperature was more than data reported by authors of equation (1).

The settlement patterns related to salinity of soils were from ground temperature changes(Miller and Johnson 1990). Soil surrounding upper half of the pile had lowersalt content, while the soil around lower half of the pile was highly saline. In early summer the creep movements were small, but when the lower portion became warm due to salt existence, expected bearing capacity was not obtained and high creep rates occurred. By start of winter the upper portion of the pile becomefrozen and the creep stopped (Miller and Johnson 1990).It was concluded that salt contents must be taken into account in the design step of pile foundations in permafrost conditions. The frozen soils creep are considerably sensitive to the pore fluid salt content and change in temperature. Test for detection of pore water salinity must be taken necessary in a routine investigation(Miller and Johnson 1990).

Piles can behave differently under seismic loading in permafrost regions. A series of shaking table tests for scale model of pile foundation in frozen soils were conducted (Wu *et al.* 2012). It was found that dynamic loading causes the frozen soil foundation in scale model present a temperature rise response. Shear deformation response in dynamic loading for the foundation showed clear resonance characteristics with dominant frequencies that were all above 15Hz. The reinforced soil did not show any resonance, and dominant frequency for that was in high frequency domain(Wu *et al.* 2012). Also,ice layers in permafrost had impact on the acceleration, dynamic earth pressure, and displacement reaction, considerably. Increase of temperature changed the seismic response of permafrost layer and pile foundation, and a heightening of acceleration input increased the response values(Wu *et al.* 2012).

2.2.Thermosyphon

Thermal pile can be defined as a pile with natural convection or forced circulationcooling system that transfers heat from the ground to the air(Johnston 1981). These thermal pile systems can use coolant circulated in the tubes, cold air blown to the pile by fluids or air convection. Also, there is a two-phase mutual alteration of vapor and condensate for that system.Thermosyphon usually is made from two-phase system,a pressure vessel filled with a singlecompound under pressure. This compound that can be propane, carbon dioxide, ammonia existsin liquid and vapor phases which are cyclically transformed to each other by absorbing and releasing heat (Clarke 2004).Thermosyphon cooling system was applied in Alaska in 1960 and was noticeably employed with over 120,000 thermosyphons installation on the Alaska pipeline in 1975 (Heuer *et al.* 1985). The early thermosyphons were made from vertically sealed tubes in the ground with surficial radiators. An example of passive cooling system and its structure by using thermosyphone in foundation of oil tanks in Alaska can be seen in Fig.8(Zarling*et al.* 1990).The vertical thermosyphon evolved to usual sloped evaporator thermosyphon or (Sloped-TF) in 1978 (Fig.9-b) and then to the flat loop thermosyphon (Fig.9-c) (Holubec 2008).Application of different thermosyphones can be as follows (Holubec 2008):

I) Thermoprobe in designation and deescription too can be used for keeping ground frozen around piles or keepingground frozen around structures.
II) Thermopile in designation and description can support structures on piles installed in frozen ground.
III) Sloped-Thermosyphon-Foundation in designation which is described as sloped evaporator pipe under slab-on grade foundations can be used to keep ground frozen below slab on grade foundation.
IV) Flat-Loop-Thermosyphon-Foundation in designation which is described as flat loop evaporator pipe under slab-on grade foundations can be used to keep ground frozen below slab on grade foundation.

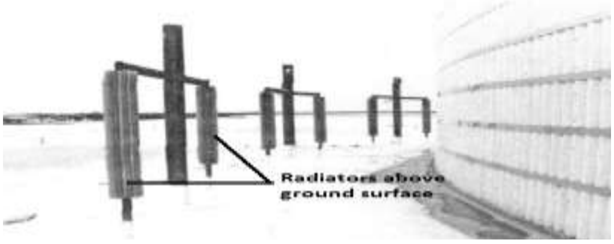

Fig.8 Typical thermosyphone structure installed in Alaska(Modified after Zarling*et al.* 1990).

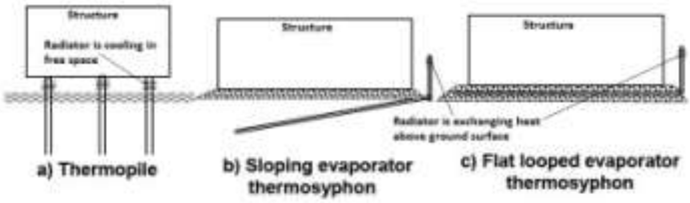

Fig.9 Three types of common thermosyphones(Modified after Holubec 2008).

Four figures below (Fig. 10) show different types of thermosyphone in practice. Flat loop thermosyphone was tested in comparison to sloped-TF in Winnipeg in 1993-1994, during winter time. It was observed that flat loop-TF could freeze 1.4 times the volume of soil compared to the sloped-TF.

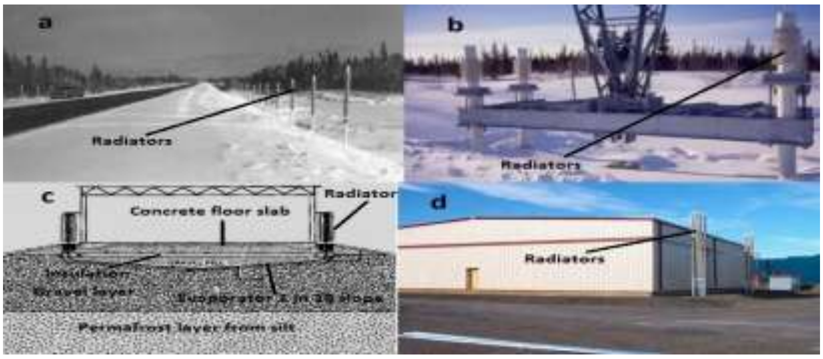

Fig. 10a)Thermoprobes (in Joe Lake, MB) for highway stabilization (Courtesy AFC), b) Thermal piles (in Manitoba DC Line, Courtesy AFC), c) Sloped thermosyphon foundation (inRoss River, YT), d) Flat loop thermosyphon Foundation (in Airport maintenance garage, Inuvik, NT, (Courtesy AFC) figures from (Modified after Holubec 2008).

After this performance, it started to widely use in Canada and Alaska from 1994 due easier installation and good performance (Holubec 2008). Hybrid system can be composed from flat-loop TF, enhanced by the addition of mechanical cooling system to accelerate and increase the rate of cooling. The hybrid system includes a cooling coil around the verticalevaporator pipe. The coil is connected to a refrigeration compressor (Fig. 11). Themechanical cooling part becomes active in warmer air temperature that condensation of thecarbon dioxide in the pipe gets difficult(Holubec 2008).

Fig. 11 Hybrid thermosyphone installation in Inuvik hospital (Modified after Holubec 2008).

III. ROAD, RAILWAY AND BRIDGE FOUNDATION IN PERMAFROST REGIONS

3.1 Considerations for road foundation

A research was conducted on an experimental air convection embankment (ACE) in Fairbanks, Alaska(Saboundjian and Goering 2003). ACE was constructed from very coarse grain 25 to 150 mm and poorly graded crushed rock that was emplaced on top of a frozen layer in permafrost. ACE with high permeability was adopted to examine the cooling efficiency of the ACE design in a real roadway. Thermistor sensor strings were used to collect temperature data from the ACE test section and a nearby section as a control area(Saboundjian and Goering 2003). They found that the ACE technique creates a passive cooling consequence by reduction of mean yearly temperature (about Δ=4°C) at the bottom of the ACE cross section in comparison to the mean temperature of embankment surface. It was observed that mean annual temperatures are considerably below freezing point at the base of the ACE, but close or above the freezing point in the upper portion of the ACE embankment. The cooling effect (Fig. 12) reduced the temperature in foundation soil beneath the embankment from above 4.4℃to near the freezing point in the 5-year observation period. In few more years by upward movement of permafrost,any seasonal thaw inthe foundation soil below will be eliminated and thaw-consolidation will be prevented in turn (Saboundjian and Goering 2003).

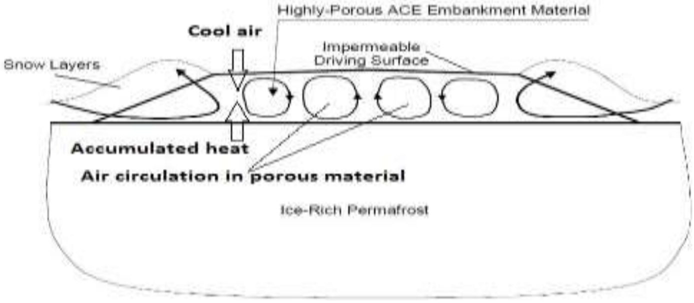

Fig. 12A schematic depiction of wintertime pore-air circulation in an ACE (Modified after Saboundjian and Goering 2003).

B analysing temperature data (Fig. 13), it was concluded that control section was colder at the embankment centerline, but warmer in the side slope region(Saboundjian and Goering 2003). It was observed that insulationlayer in control section can reduce the annual temperature in soil beneath the embankment centerline. Although, considerable yearly thaw was happening in the side-slope region inside the foundation soils under the control section. Thaw in control section side-slope resulted in major distortion and shoulder rotation, while no sign of distortion at either shoulder of ACE embankment was observed (Saboundjian and Goering 2003).

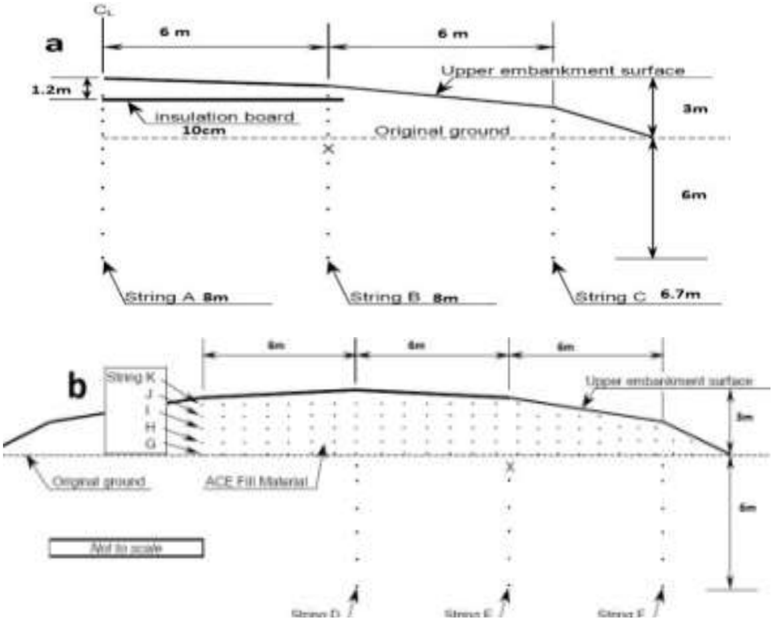

Fig. 13 Positions of thermistors in strings A to C in control section and strings D to K in ACE located within and below the embankments (Modified after Saboundjian and Goering 2003).

Three types of passive cooling methods were applied in Thompson Drive in Alaska to control the thermal stability of permafrost beneath the highway(Xu and Goering 2008). These methods were ACE layers, ventilated shoulders using crushed rocks and boulders, and two-phase hairpin thermosyphons. The hairpin thermosyphons (Fig. 14) is a novel design that keeps both the condenser and evaporator concealed under the ground surface. Older models of road thermosyphons use air-cooled condenserswith finned heat exchangers reaching above ground surface in contact withfree air. By using hairpin design, problems such as high-cost of air-cooled heatexchangers and the safety and esthetic concerns are avoided. Heat flux and temperature data obtained from the hairpin thermosyphons confirmed its efficiency for eliminating heat from subgrade soils underneath the embankment(Xu and Goering 2008).

Fig. 14 Hairpin thermosyphon condensers used in Thompson drive, Alaska (Modified after Xu and Goering2008).

A review on different methods and their costs in stabilizing roadbed in permafrost areas was performed (Regehr*et al.* 2012). These methods were classified to four categories: (I) methods thatcontrol roadbed thawing; (II) methods thatcool the roadbed; (III) methods thatinsulate the roadbed;
and (IV) methods thatreduce roadbed fill weight.

Two types of techniques for category (I) were suggested. Prethawing or thawing before construction of an embankment by removal of the topsoil and vegetation, and exposing underneath permafrost was one of those techniques. Thawing after construction of road embankment by embankment widening and snow removal another technique(Regehr*et al.* 2012). Six methods in category (II) were found, which are used broadly to cool the roadbeds and are well documented especially in Qinghai-Tibet Railway. These techniques include (a) reduction of solar radiation by different covers; (b) construction of air convection embankments; (c) utilization of ventilation ducts; (d) application of thermosiphons; (e) application of heat drains; and (f) methods to control heatconduction. One or combination of above methods can be used to achieve desirable results too (Regehr*et al.* 2012). Category (III) can be applicable by insulation that made from polystyrene or polyurethane foam. The insulation material is emplaced near to the surface of the roadbed in a layer form. To apply category (IV) strategy, light weight fill material withlower density than typical soils and rock and even as low as 12 kg/m^3 can be used. The light weight fill material could be expanded polystyrene (EPS) blocks, foamed (or cellular) concrete, rubber tire fills from shredded or crumbed tires, and organic fills (peat) or combination of them (Regehr*et al.* 2012). It was concluded that cost of above improvement techniques includingtransport costs changes in different geographic and climatic conditions.Betweenmethods to cool the roadbed, air convection embankments and ventilation ducts had lower capital costs. Installation of reflective surfaces and shoulder ACEs had lowest life-cycle cost perspective(Regehr*et al.* 2012). Generally techniques to controlthawing, insulate the roadbed, and reduce roadbed fill weight had lower capital and life-cycle costs than roadbed cooling techniques. Sometimes do-nothing procedure compared to above techniques can be considered by taking different strategies cost, and expected serviceability into account(Regehr*et al.* 2012).

3.2 Considerations for railway foundation

Several hazards for railway structure were found Qinghai–Tibet railroad (QTR) project in permafrost area (Wei *et al.* 2002). Geotechnical problems such as frost heave and thaw settlements, frost mound, icing, gelifluction were some of those hazards. They found that cooling of railway bed by different techniques were most applicable in QTR project. These methods included regulating and controlling of solar radiation (Fig. 15a), regulating and controlling heat convection by crushed rocks (Fig. 15b), ventilation ducts (Fig. 15c), thermosyphons (Fig. 15d), and controlling heat conduction by embankment with turf revetments or combination of above methods(Wei *et al.* 2002). Different embankment designs and fillings as the low cost options were used to adjust and control heat transfer in QTR project (Fig. 16) (Cheng *et al.* 2009).

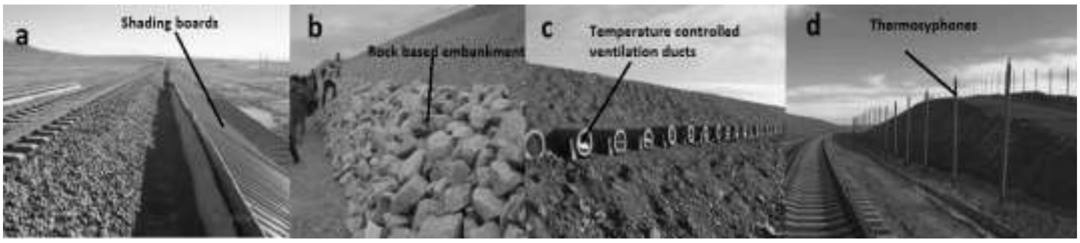

Fig. 15: Different cooling methods in Qinghai–Tibet railroad project. a)Shading boards; b) Rock-based embankment; c) Embankment with temperature-controlled ventilation ducts; d)Thermosyphones(Modified after Wei *et al.* 2002).

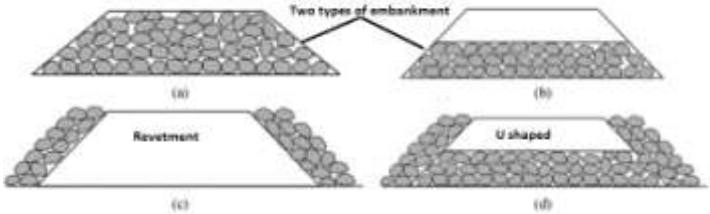

Fig. 16 Different configurations for crushed rock embankment in QTR project. (a&b) Crushed rock embankment; (c) crushed rock revetment; (d) crushed rock U-shaped embankment(Modified after Cheng *et al.* 2009).

3.3. Considerations for bridge foundation

A case study for replacing a railway-bridge at Goldstream Creek, Alaska is discussed here. A frozen silty soil was widespread in the valley, experiencing thawing because of some factors(Krzewinski and Ross 2013). Thawed ground movement toward the creek channel was inducing slowly inward translation of former bridge and tilting of the foundations. This was causing adistortion in the super-structure. For supporting the new bridge driven steel piles and passive refrigeration by installing thermosyphons inside the steel piling were applied(Krzewinski and Ross 2013). Refreezing of surrounding soils had ability to increase the lateral and vertical capacities of the pile foundation(Krzewinski and Ross 2013).Groups of (41 cm) diameter steel driven pile arranged in two rows. They includedtwelve piles at the Pier, and six piles at each abutment for new bridge foundation. Piles were installed open-ended to depths of 18 to 21 mfrom the ground surface passing frozen silt and resting on a sandy layer(Krzewinski and Ross 2013). Capacities of piles in ice rich soils relies on several factors such as temperature, rate of loading, ice content, and soil type. Axial capacity of piles were formed from arrangement of the adfreeze bond laterally from pile perimeter and an end bearing in the sand layer which were smaller comparably (Krzewinski and Ross 2013).

Lateral capacity of piles were calculated considering two scenarios by using a non-linear material properties and p-y curves, a mutual relation between soil reaction (p) and lateral pile deflection (y). Two considered scenarios were: a) a completely frozen layer in the height of winter conditions, and b) when the thawed active layer is in its maximum thickness in late fall(Krzewinski and Ross 2013).Thermosyphons were mounted inside 6 out of 12 piles, and inside 4 out of the 6 piles at abutment, alternatively. Radiators were installed horizontally (Fig.17) with some slope on piles while thermosyphon condensers had 6 m^2 condenser area.It wasconcluded that this railroad bridge was first in its own to use thermosyphons for passive refrigeration of its foundation and surrounding soils(Krzewinski and Ross 2013). Good performance for the bridge after construction was reported.

Fig.17 Thermosyphone condenser installation on bridge pier piles (a: courtesy of Arctic Foundations Inc, and b: courtesy of Alaska Railroad Corporation's)(Modified after Krzewinski and Ross 2013).

Construction of dry bridges in total length of 125 km were reported in QTR project (Fig.18)(Wei *et al.* 2002). Piles of 1.2 m in diameter were installed in 25–30 m depth from ground surface that produced a robust foundation with deformations of less than 2 mm (average) and 5 mm (maximum) after operation.

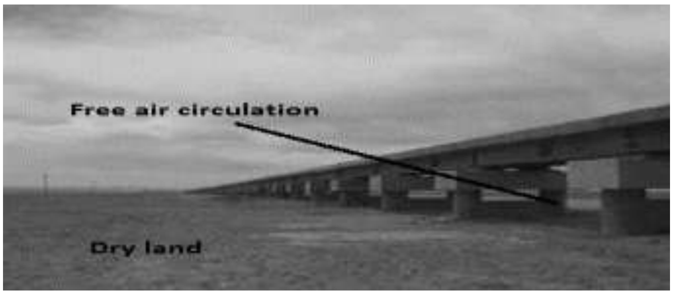

Fig.18 An example of dry bridge in Qinghai–Tibet Railway (QTR) project(Modified after Wei *et al.* 2002).

Dry bridges can act as a shade and reduce the ground temperature in combination with air flow below them. They can tolerate heavy loads and create required stability in sensitive permafrost. Wild animals can easily pass railroads or highways (Wei *et al.* 2002).

4.Pipeline foundation in permafrost areas

Pipeline projects in permafrost need more geotechnical consideration than temperate lands. Geotechnical considerations are different among gas and oil pipelines and include geothermalimpact on the ground, route and train technical analysis, controlling permafrost conditions, slopes design for pipe, impact of frost heave and thaw settlement on pipe and their moderation(Oswell 2002). Gas pipelines can experience the Joules-Thompson effect, cooling of the gas from decompression between compressor stations. This cooling can be beneficial in discontinuous permafrost. Generally gas is chilled below freezing point to contain more gas in higher density for transport in permafrost.Oil sometimes is transported without heating in pipeline since itsflow point is –14℃. But there are cases that oil is heated to 50℃ to 60℃ for high volume transport in buried pipeline(Oswell 2002).The pipeline below freezing point keeps stability of permafrost slopes, and enhances buoyancy control and restraining the pipe by the frost bulb around the pipeline. The geographic location in which the pipeline set-up changes from below freezing point to above freezing is called the “last point of cold flow” usually lies in transforming zone from permafrost to non-permafrost zone(Oswell 2002).The transition zone can be detected by geophysical, and geotechnical investigations. With mentioned transition, frost heave and thaw settlement problems should be considered simultaneously. Mitigation techniques for thaw settlement and frost heave can be different based on project and time of identification. In design step, re-routing is one of the best methods to avoid those hazards. Excavation and filling with thaw stable materials, insulation, pipe temperature control,ground water control and support above ground surface are some preventive methods for thaw settlement and heave frost (Oswell 2002).A numerical modelling was conducted to study thermal effects under permafrost conditions in the Chinese–Russian crude oil pipeline(Zhang *et al.* 2010). Two types of transfer, conventional pipeline burial mode and pipeline on aboveground embankment were modeled. Two methods for thermal control e.g. bare and insulated pipeline along with three climate conditions were considered. In climate conditions average ground surface temperatures of −0.5, −1.0, −1.5 °C, along the pipeline in the next 50 years period were applied in modeling(Zhang *et al.* 2010). It was concluded that in all the climate conditions and the thermal control methods in buried pipeline mode the permafrost table goes down constantly after start of pipeline usage (Fig.19a). Although,in aboveground embankment pipeline, permafrost table under embankment rises in the first decades, then goes down when operationtime goes further (Fig.19b) (Zhang *et al.* 2010).

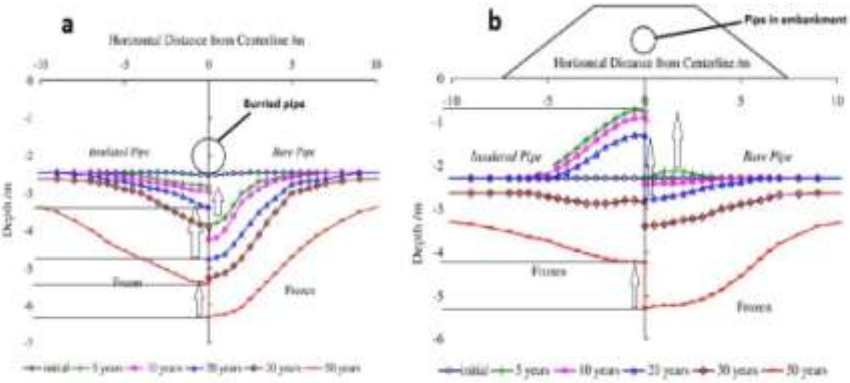

Fig.19 Progress of thaw plugs under bare and insulated pipeline in mean ground surface temperature of −0.5 °C a) under buried pipeline b) under embankment pipeline(Modified after Zhang *et al.* 2010).

It was also concluded that in the embankment mode by thermal control methods, thawing of permafrost can be prevented in the service life of the pipeline. However, in usual buried pipeline method, the thawing of the permafrost cannot be prevented in all the assumed climatic and insulation conditions(Zhang *et al.* 2010). Backfilling with non-frost-susceptible soils, and/or utilization of thermosyphons in the buried pipeline method is recommended in the warm and ice-rich permafrost conditions to guarantee pipeline stability (Zhang *et al.* 2010). Takashi’s equation [Eq. 2] for frost heave prediction and numerical modeling to evaluate the maximum bending strain and stress for structural design was used for pipeline structure (Kanie*et al.* 2006).

$$\xi = \xi_0 + \frac{100\sigma_0}{\sigma}\left(1+\sqrt{\frac{U_0}{U}}\right) \qquad [2]$$

In Takashi’sequation ξ is frost heave ratio;σ is overburden pressureand *U* is freezing rate.
ξ_0 (%), σ_0 (kPa) and *U0* (mm/hr.) are three experimental constants.

Numerical modeling by above equation predicted frost heave withreasonable accuracy.It was concluded that load intensity from frost heave can be assumed with a constant distribution along the pipeline in non-permafrost area(Kanie*et al.* 2006). In non-permafrost end, Takashi’s equation with two dimensional analysis of heat transfer can predict frost heave in freezing season. The distributed load (Fig. 20) which was calculated with two dimensional analysis of heat transfer but without considering creep effect demonstrated good concurrence with the observed results in reality(Kanie*et al.* 2006).

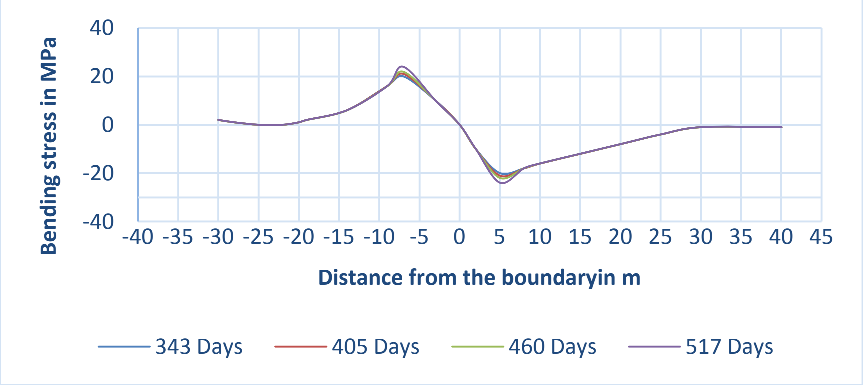

Fig. 20 Analyzed bending stress (Modified after Kanie*et al.* 2006).

IV. CONCLUSION

Permafrost areas cover close to a quarter of earth surface and many projects have been or will be constructed in the permafrost. From a comprehensive review on geotechnical problems and solutions in different civil projects in permafrost regions (e.g. building foundation, roadway, railroad, and pipeline) following conclusions can be drawn. A special geotechnical engineering for permafrost projects is necessary to avoid main geotechnical problems. Historical and new projects are approval for existence of these geotechnical problems and necessity of mitigation methods for future projects. Depending on type of project, active or passive cooling systems and thaw resistant techniques or combination of them should be applied to build a stable structure in the permafrost regions.These techniques will be functional by following considerations: reduction of solar radiation by different covers, lowering of pore space occupants temperature or soil temperature by refrigerating, enhancing air convection, utilization of ventilation ducts, heat drains, thermosiphons, reduction of heat conduction, and using of thaw stable fill materials. Each or combination of above considerations can be applied in permafrost projects depending on project type, requirements, and budget.

ACKNOWLEDGEMENT AND DECLARATION

Authors want to declare hereby that sources of all images and other authors work have been cited. First author want to appreciate University of Ottawa for providing financial aid in the form of PhD admission scholarship.

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