1 Northwest Territories Thermosyphon Foundations in Warm Permafrost— Building Resources Infrastructure

1.1 Background

As part of the First National Engineering Vulnerability Assessment, the Public Infrastructure Engineering Vulnerability Committee and the Government of the Northwest Territories Public Works and Services contracted I. Holubec Consulting Inc. to examine and report on the implication of climate warming on permafrost, ground temperature and foundations.

The consultant produced one of seven case studies included in this First National Engineering Vulnerability Assessment Report. The series of case studies examines the vulnerability and adaptive capacity of infrastructure to climate changes. This case study, on thermosyphon foundations in warming permafrost, is one of two on buildings commissioned as part of the National Engineering Assessment of the Vulnerability of Public Infrastructure to Climate Change. While the six other case studies focus on infrastructure at one site or within a limited geographic area, this case study uniquely assesses information from a number of locations across northern Canada.

Figure A-10 Visitor Centre, Inuvik

Permafrost and Current Responses in Infrastructure Design

Permafrost – consisting of soil, rock, organic material and ice lenses that remain frozen below 0°C for at least two consecutive years – is a common phenomenon throughout northern Canada. Even in very cold climates, the ground temperature in permafrost does not fall below approximately -10°C.

In regions with permafrost, the very top layer thaws and freezes every year. Observations in recent years show that the depth of this active layer is increasing. As with soil, clay and rock, the composition of permafrost varies greatly from one location to another. These variations in permafrost properties and the fact that it can thaw when exposed to increased temperatures and precipitation present challenges when designing infrastructure. Traditionally, design considerations focused especially on preventing heat from the infrastructure melting the permafrost supporting structures. Failure to avoid such permafrost melting can leave infrastructure, including buildings, vulnerable to settling into the ground.

Historically, design features to prevent the permafrost from melting and to avoid the infrastructure settling have included:

- Placing the structures on natural rock, wooden or concrete blocks; or
- Positioning the structures on pilings – usually made of wood or steel. The pilings then are held in place by a wet-sand slurry that freezes the piloting in place under ground.

These approaches create a space between a building or other structure, and the ground. This spacing prevents heat from the infrastructure melting the permafrost.

These methods are relatively effective in preventing infrastructure settling in "cold" infrastructure regions but have proven to be less effective in "warm" permafrost areas where the ground temperature reaches -2°C or higher.

There is increasing evidence that besides heat from infrastructure thawing permafrost below, atmospheric climatic warming is extending:

- the "warm" permafrost regions and
- the areas without permafrost.

In parts of the Arctic, unless preventive measures are taken, this increases the vulnerability to settling both of existing structures and future infrastructure.

Thermosyphon systems, a major focus of this case study, offer a means of preventing permafrost near infrastructure from melting. Such systems extract heat from the ground, and so avert settling and help maintain the integrity of the infrastructure. First used in Alaska in the 1960s, variants of these installations are found at close to 160 sites in Canada's North. Russia also employs such systems Thermosyphon systems may be further adopted to stabilize foundations as the areas where the permafrost continues shrink. Use of thermosyphons would be enhanced by:

- Better understanding of such systems; and
- Availability of more reliable information on how climate change affects ground temperatures.

1.2 Technical Summary

Permafrost and Relationship With Air and Ground Temperature

In permafrost regions, for the first 10–15 cm below ground level, ground temperature fluctuates with air temperatures. Below this 10–15 top zone, there is zero annual amplitude (or change) in temperature and the area is characterized as being permafrost The ground temperature at the point of zero amplitude depends on the mean annual air temperature and the type of ground cover. According to the Geological Survey of Canada, generally the mean annual temperature at the ground surface is about 4.4° C warmer than the mean annual air temperature. The mean annual ground temperature at the point of zero amplitude is normally the same as the mean annual ground temperature.

Increases in the average air temperature will impact the ground temperature. However, ground temperatures also depend on other factors, such as the vegetation cover, terrain (including the slope), winter snow cover, mineralogy, and the water/ice saturation in the ground or soil.

Observations indicate that average Arctic temperatures are increasing at twice the global average. Also, according to the Intergovernmental Panel on Climate Change's *Climate Change 2007; The Physical Science Report*, the temperature at the top of the permafrost layer in the Arctic has generally increased by 3°C since the mid-1980s. The average temperature varies by regions within the Arctic. Furthermore, climate models predict that such average temperature increases will continue until 2100.

Rises in the average atmospheric temperature that raise ground temperatures above 0°C can be expected to turn regions of "cold" permafrost into areas of "warm" permafrost (locations where ground temperature reaches -2°C or warmer). It will also reduce the total area impacted by permafrost. For both existing and future infrastructure, this extends the area where structures built on permafrost are vulnerable to settling.

This case study presents 2006 information on mean annual air temperature and mean annual ground temperature (extrapolated by adding 4.4°C to the mean annual air temperature) at 17 climatic stations within five permafrost regions (Yukon; Western Arctic and Mackenzie Valley; Central Mainland Arctic; and Eastern Arctic and Arctic Islands). The case study also reports on the warming rates of mean annual air temperature and mean annual ground temperature since 1985 for these locations.

Thermosyphon Systems

Thermosyphons are passive systems without power requirements or moving parts. They utilize two-phase liquid-vapour and convection heat-transfer devices to extract heat from the ground and release it to the atmosphere. The lower portion of the thermosyphon is installed in the ground and serves as an evaporator, and the above-ground portion acts as a condenser. Where used in buildings, insulation above the evaporator pipes slows the heat flow from the building towards the foundation. The thermal properties and thickness of the insulation minimize the introduction of heat into the cooled foundation so that the foundation remains frozen the summer when the thermosyphons do not operate.

Thermosyphon cooling first was used on communications towers in Alaska, starting in the 1960s and similar systems then were adopted for the Trans Alaska Pipeline Systems, where 120,000 thermosyphons were positioned to prevent pipeline supports from settling. Since 1985, approximately 160 thermosyphon systems have been installed at sites in Canada's three northern territories (mostly in the Northwest Territories and Nunavut) as well as in Quebec, Manitoba and Ontario. They have been installed from Thompson, Manitoba, (55° 48'N, 97° 22W) in the south, and north as far as Alert, Nunavut (82° 31N, 62° 17W). These areas have respectively means annual air temperature of -3°C and -18°C.

Canada's first thermosyphons installations were vertical probes used to maintain permafrost around earth embankment. Related solutions in the form of thermopiles and sloped thermosyphons kept structures supported on frozen ground.

Development of more efficient and easier-to-install flat-loop thermistors resulted in increasing use of this innovation at permafrost sites. Since 1994, about 80 such flat-loop systems have been used – mostly for buildings (65) and the rest on dams (15) – to stabilize foundations built on permafrost.

This case study draws on information 11 from thermosyphon projects at 10 sites in northern Canada. They included thermosyphon foundations at three Inuvik, N.W.T. locations – the Female Young Offender Facility, Visitor Centre and Inuvik Hospital – as well as a school in Rankin Inlet, NU. Two detailed thermosyphon case histories from the Yukon – an ice rink in Dawson City and a school at Ross River also were among those reviewed.

The consultant found that in the few cases where buildings supported by thermosyphon foundations functioned poorly, it related to: a) poor design/construction of the granular pads on which the thermosyphon evaporator pipes are founded; b) inadequate construction details, construction scheduling; and c) inadequate insulation design. The case histories of installations with problems do not challenge the thermosyphons foundation design concept but demonstrate the need to improve the design, construction and monitoring of this foundation design.

1.3 Policy Makers Executive Summary

Findings and Observations

Ground-temperature information is important in determining the condition of permafrost and its capacity to support infrastructure.

There is a general lack of such ground-temperature data and, where accessible, it is only available from scattered locations. In the absence of data, a Geological Survey of Canada approach based on average air temperatures being 4.4°C cooler than the mean ground temperature has been used to estimate the latter. However, there are no standards or guidelines available to estimate the design factors relating to air temperatures, climate warming and ground temperatures. Given increased climate warming, the normal values provided by Environment Canada covering 1970–2000 do not reflect present air temperatures and the length of the freezing season.

Climate information from Environment Canada used by the consultant shows that permafrost temperatures in 80 per cent of 17 representative communities examined in the case study are in the -1°C to -5°C range. Based on projected warming trends, it means the ground will start to thaw within the life span of buildings constructed within the last decade. The severity of the impact on infrastructure will depend on underlying ground conditions and building design.

Buildings in these communities generally are designed to stay stable to a temperature of -2°C. A number of the communities have ground temperature of this value and foundations are showing sign of changes in the magnitude of heaving and settlement. Responses to these conditions have included:

Figure A-21 Permafrost layers

- Locating the buildings on bedrock or ice-free ground underlain by bedrock;
- Using end-bearing piles extending below the ice-rich soil and with designs that allow for settlement correction at the pile cap; and
- Installing thermosyphon foundations.

Thermosyphon systems, which allow permafrost to be kept frozen, have been used since the 1960s. A variant, the flat-loop thermosyphon system used in foundation designs, has been installed in Canada since 1994. Depending on the effective warming of temperatures, both in winter to allow proper re-freezing, and in summer to avoid too much thawing, flat-loop thermosyphons can permit ground to remain frozen for the life span (50 years) of the building.

The current case study – drawing from Canadian sites, the consultant determined that except for six sites studied that had design or construction or materials-quality problems, thermosyphon systems are performing effectively. However, the consultant notes that limited performance records are available and generally are limited to less than one year at most installations.

Thermosyphons cooling systems must be monitored regularly to ensure proper operation. Currently guidelines/standards are not available for design, construction and monitoring of such systems. (See recommendations below.)

Recommendations

The consultant makes several recommendations to better assess the vulnerability and adaptive capacity to climate change of infrastructure foundations in permafrost regions.

Key recommendation centre on preparing guidelines for the collection of data, design, construction, operation, maintenance and monitoring of thermosyphon foundations. The resulting information should be applied to thermosyphon systems now in place and those that will be built.

Specifically, the following recommendations are made.

1) Establish design air temperature and climate warming criteria. This would allow present “normals” and climate warming rates to better reflect the current rates (with “normals” being about 2°C warmer) rather than relying on historic data from 1970 to 2000.
2) Prepare guidelines for geotechnical investigations and collection of design information. Deeper drilling (than the 8 to 10m now common) during initial investigation would provide better information for designing appropriate foundations for permafrost

experiencing warming. It would also allow installation of temperature sensors at greater depths, where there are only minor temperature fluctuations.

3) Conduct a calibration and parametric thermal analysis study of thermosyphon foundation design at typical sites to better understand robustness of this design. Such study would provide information on the best combination of design measures (e.g., insulation thickness, evaporator pipe spacing, radiator lengths, pad thickness and saturation) to deal with climate warming.
4) Identify codes and standards that apply to thermosyphon piping. Since thermosyphon piping is a pressure vessel, a qualified engineering firm specializing in pressure vessels should report on this subject.
5) Prepare design and construction guidelines for thermosyphon foundations to inform designers, architects, geotechnical engineers, contractors, inspectors, reviewers and project owners. Issues dealt with by the guidelines would include; foundation pad design, surface and groundwater control, design and location of services within granular pad in slab-on-grade design, as well as construction materials, scheduling and controls.
6) Prepare guidelines for the instrumentation and monitoring for buildings with thermosyphon foundations. The guideline would include information on the design and location of temperature sensors in the ground, the evaporator pipes and radiators. Guidance should be offered for analyzing the resulting data.
7) Preparation of baseline documentation at key existing thermosyphon foundations for monitoring and future studies.