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Seasonal thermal insulation to mitigate climate change impacts on foundations in permafrost regions

P. Perreault, Ph.D., PE *, Y. Shur

Department of Civil and Environmental Engineering, University of Alaska, Fairbanks 306 Tanana Drive, Duckering Bldg. Room 245, Fairbanks, AK 99775, USA

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ABSTRACT

Climate change impact on existing infrastructure built on permafrost is of concern to many engineers and scientists. Some studies predict widespread collapse of the existing infrastructure. Adapting structures in the permafrost region to climate change is an important contemporary issue. In this paper, we analyze impacts of permanent and seasonal thermal insulation on permafrost temperature. An analysis of the available data shows that permanent thermal insulation increases the permafrost temperature when the soil surface is exposed to seasonal air temperature variations and when the mean annual soil surface temperature is below 0 °C (32 °F). We study the thermal impact of seasonal insulation applied in the spring and removed in the autumn to restrict summer heat flow into the ground. The absence of thermal insulation in winter permits soil cooling. We present the results from two-dimensional thermal analyses of a building in the discontinuous permafrost zone. These results show the effectiveness of seasonal thermal insulation. Summer seasonal thermal insulation on the soil surface in a ventilated crawl space decreases permafrost temperature and can be valuable for increasing foundation integrity in a warming climate. The impact of seasonally installed thermal insulation on permafrost increases as the thawing index increases. Seasonal thermal insulation is especially valuable in the discontinuous permafrost zone, where bearing capacity of shallow foundations and adfreeze strength of frozen soil with piles are sensitive to minor soil temperature changes.

The method is adaptive and flexible, and the initial cost is low, all of which are important considerations given the uncertainties of climate warming. Using seasonal insulation permits an incremental response to future climate warming conditions as they occur.

1. Introduction

The impact of climate change on existing structures in the permafrost region is an ongoing concern for Arctic engineers and permafrost scientists (Nixon, 1994). Damage to existing infrastructure, even its total collapse because of reduced foundation bearing capacity was predicted (Khrustalev, 2001). Several studies have already attributed structural building distress and failures to permafrost warming (Kronik, 2001). The necessity and means of mitigating the impact of climate change on permafrost are discussed in Grebenets et al. (2012) and in Vyalov et al. (1993a).

Increases in permafrost temperature can cause significant loss of soil bearing capacity and increase frost heaving forces on foundations (Osterkamp, 2003; Grebenets et al., 2012; Vyalov et al., 1993b; Andersland and Ladanyi, 2004). The bearing capacity of shallow foundations and the adfreeze strength of piles in permafrost are a function of soil temperature. Permafrost strength decreases as permafrost temperature increases. Vyalov et al. (1993b) evaluated change in adfreeze strength of piles in permafrost for mean annual air temperature increases of 2 °C (3.6 °F) and of 4 °C (7.2 °F). These results are summarized in Table 1.

Data in Table 1 show that an increase in mean annual air temperature of only 2 °C (3.6 °F) can be damaging to buildings in the areas of warm permafrost with temperature above −3 °C, which is typical for the discontinuous permafrost zone.

Current engineering methods to protect the frozen state of soil under structures include open ventilated crawl spaces, thermosyphons, ventilated ducts, and clearing snow from a construction site before work begins (Long and Zarling, 2004). Vyalov et al. (1993b) found that combining a ventilated crawl space and thermal piles (pipe piles that include thermosyphons) is especially effective in permafrost protection. Implementing mitigation measures for new building projects is easier and less expensive than for existing structures. For example, installing thermosyphons in new foundations may be more economical without the physical constraints of from construction overhead. In contrast, owners of existing buildings may need to pay a premium for horizontally-installed thermosyphons because the installer no longer has easy access to the more-limited space below the building (Khrustalev, 2001).

Abbreviations: ACIA, Arctic Climate Impact Assessment; MAT, Mean annual soil temperature; FAI, Fairbanks International Airport.

* Corresponding author at: P.O. Box 82548, Fairbanks, AK 99708-2548, USA.
E-mail addresses: pvpengineer@ak.net (P. Perreault), yshur@alaska.edu (Y. Shur).

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Table 1
Adfreeze strength decrease with warming permafrost (based on Vyalov et al., 1993a).

Permafrost temperature	Decrease in adfreeze strength (%) with increase in mean annual air temperatures	
(Tp)	Warming	Warming
	2 °C	4 °C
0 °C to −1 °C (32 °F to 30.2 °F)	50 to 100	100
−1 °C to −3 °C (30.2 °F to 26.6 °F)	20 to 30	40–53
−3 °C to −7 °C (26.6 °F to 19.4 °F)	8 to 17	35–50
<−7 °C (<19.4 °F)	<3	3 to 16

Two different approaches can be outlined for dealing with climate change impact on new infrastructure. One approach is to design for the worst-case warming scenario based on current understanding. This approach increases new-construction costs. The second approach is an optimization of the lower new-construction costs with risk-management considerations that may lead to additional costs later. Choosing the second approach has some benefits but involves responsibilities. While the cost of new construction is lower, the owner must remain vigilant to site-specific thermal conditions (Khrustalev, 2001). Nixon Geotech Limited (1994) solicited opinions of practicing engineers and scientists on two questions: (A) "Can predictive systems for the effects of climate change be developed, and (B) would they be useful and practical for input to the design of engineering projects in the north?" Among many thoughtful answers to these questions, the one by K.R. Croasdale & Associates caught our special attention. It says "climate warming should be accommodated in design on a 'what-if' basis, but the procedure of incorporating it in the design process must be flexible to allow for changing observations and climatic conditions with time" (Nixon Geotech Limited, 1994, p. 5).

Contemporary discussions on mitigation of climate change impacts on infrastructure omit the effects of thermal insulation. Effects of natural thermal insulation such as moss, peat, and snow on permafrost are well known. Moss and peat greatly reduce permafrost temperature compared with a bare soil surface and stimulate permafrost development. Snow, on the other hand, increases mean annual soil temperature everywhere in the permafrost region and is a very important factor in permafrost absence and degradation in the discontinuous permafrost zone. Moss and peat represent a natural permanent thermal insulation that undergoes seasonal changes in its thermal properties. Snow is an example of a natural seasonal thermal insulation.

1.1. Permanent insulation

Thermal insulation has a long history of applications in engineering projects (Andersland and Ladanyi, 2004; Esch and Rhode, 1976; Farouki, 1992; Johnston, 1983). It has been used in areas with seasonal freezing of soil as well as in permafrost regions to minimize seasonal soil freezing and to reduce the thickness of the active layer. Thermal insulation prevents or minimizes frost heave impact on foundations and reduces the risk of freezing utility lines. Insulation can sufficiently reduce a thaw bulb under heated buildings constructed according to the "active method" which allows permafrost thawing beneath buildings and other heated structures. It was shown that thermal insulation could greatly reduce permafrost thawing under heated buildings without a ventilated crawl space (Porkhaev, 1970) and under warm pipelines (Shur et al., 2004). The permanent thermal insulation can greatly reduce the active layer thickness and reduce the depth of seasonal soil freezing in areas without permafrost. It is very important means in decreasing the depth of shallow protected foundations (Farouki, 1992). An impact of permanent insulation on soil temperature in conditions of seasonal temperature changes on the soil surface is not so obvious. It is widely believed that permanent insulation also decreases permafrost temperature under unheated structures as roads and airfields. For example, Doré and Zubeck (2009, p. 381) stated: "The purpose of the embankment insulation is to prevent temperature increase." Several field studies do not support such a conclusion. Pavlov (1975) studied thermal insulation impacts on soil temperatures in Yakutsk, Russia, and showed that permanent thermal insulation under an unheated surface exposed to air increases, not decreases, permafrost temperature. In his studies at a snow-covered site, the increase was relatively small (from 0.4 °C to 0.6 °C or 0.7 °F to 1.1 °F). Without snow, however, the increase in soil temperature was much greater (4.5 °C or 8.1 °F). Pavlov concluded: "Constant thermal insulation on the soil surface has a warming impact in areas with mean annual air temperatures below 0 °C (32 °F) and cooling effect in areas with mean annual air temperatures above 0 °C." (Pavlov, 1975, p. 266).

Esch and Rhode (1976) described a temperature regime under the permanent insulation at the Kotzebue Airport in Alaska. They found that soil at a depth of 6 m (19 ft) at insulated sections was 1 °C to 2 °C (1.8 °F to 3.6 °F) warmer than at a control section without thermal insulation.

Nidowicz and Shur (1998) analyzed permafrost temperature data presented by Johnston (1983). The data was from beneath a road with permanent insulation at Inuvik, Canada. Over four years of the experiment, the average temperature under an insulated road section was about −5 °C (23 °F) at a depth of 2.5 m (8.2 ft). Under the uninsulated control section, the average temperature was about −8 °C (17.6 °F). This study also showed an increase in permafrost temperature under permanent thermal insulation.

Permanent insulation was used to prevent permafrost degradation and reduce frost heave for a railroad track about 60 km (37.3 mi) south of Fairbanks, Alaska (Trueblood et al., 1996). After five years, the soil temperature at the site located in the discontinuous permafrost zone was no cooler than the soil temperature in areas without insulation.

Understanding the impacts of permanent thermal insulation on the structural integrity of roads, airfields, and buildings with a ventilated crawl space in cold regions, requires understanding its effects on the active layer separately from its effects on permafrost temperature. The thermal insulation reduces the active layer thickness on the one hand and can increase permafrost temperature on the other hand. In the continuous permafrost zone where the permafrost temperature is usually below −5 °C (23 °F) permanent insulation under roads and airfields can greatly reduce the active layer depth. The permafrost table often rises under an embankment. Increases in permafrost temperature, on the other hand, are often not critical in such continuous permafrost conditions. A decrease in the active layer depth decreases the frost heave impact, and the cumulative effects of thermal insulation are beneficial.

By contrast, using permanent thermal insulation in a crawl space below a building with a pile foundation may be an unwise decision. Under the building, the permafrost bearing capacity depends on soil temperature. The permafrost temperature is more important for foundation support that for soil beneath roads. Foundation stability for buildings either depends upon permafrost bearing capacity for shallow foundations, or depends upon the adfreeze strength between the foundation piles and the permafrost. Both depend greatly upon the maximum permafrost temperature during the yearly cycle. For buildings with permanent insulation in the crawl space, an increase in permafrost temperature and the accompanying strength-reduction from warmer permafrost becomes salient.

Some sources recommend applying permanent thermal insulation in the crawl space without taking into account that such insulation can compromise the bearing capacity of foundations. For example, USSR building code SN 91-60 (1963) had this requirement: "Thermal insulation layers should be used to cover the soil surface in the ventilated crawl space with (slag, wood panels etc.) and around the structure to