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Incorporating climate warming scenarios in coastal permafrost engineering design – Case studies from Svalbard and northwest Russia

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ABSTRACT

Climate change is predicted to strongly affect the evolution of the Arctic coast over the coming decades. The continuous warming trend observed in Svalbard and northwest Russia since the 1980s are creating concerns related to the stability and durability of existing infrastructure on permafrost and uncertainties related to the design of new structures and infrastructure in the region. An increase in ground temperatures may reduce the bearing capacity and increase settlement rates and subsidence of foundations, and stability of natural and engineered slopes. The effect of climate warming in permafrost regions may cause unacceptable risks according to existing engineering design criteria. A methodology is suggested where the output from climate models can be used as input to engineering models assessing change in the ground thermal regime at site specific locations in permafrost regions. The main objective has been to determine the computed warmest ground temperature occurring during the service life time of the structure, taking climate warming scenarios into consideration. This type of information can be used in coupled thermo-dynamic and mechanical models of the local geotechnical site conditions including structural elements such as foundations, port structures, transportation systems and pipelines. Site specific data from statistical downscaling of General Circulation Models (GCMs), and soil and permafrost data from research sites in Svalbard and northwest Russia has been used in a transient geothermal model to compute possible future ground temperatures in the areas. The results show that depending on the soil conditions and current permafrost temperatures, the sensitivity to climate warming vary from small or negligible to considerable. Further development of the methodology advocates a probabilistic approach.

1. Introduction

This study is a part of an ongoing research program carried out at the Norwegian University of Science and Technology (Finseth and Instanes, 2012) (see http://www.ntnu.edu/samcot). The research program focuses on developing guidelines and new technology needed for industrial development in the coastal areas and marine environment in the Barents region. Of special interest are landfall areas for pipelines from offshore oil and gas fields in the Pechora and Kara Sea, and development of harbours along the permafrost shores of Svalbard and northwest Russia.

Climate change is projected to strongly affect the evolution of the Arctic coast over the coming decades (Forbes, 2011). Permafrost coasts are especially vulnerable to erosive processes as ice inclusions in the soil layers beneath the seabed and shoreline thaws from contact with warmer air and water. Thaw subsidence at the shore allows additional wave energy to reach unconsolidated erodible materials (Instanes et al., 2005). Climate change together with human interaction and industrial development in Arctic coastal areas can affect the temperature regime within permafrost soils, resulting in increased creep rates, erosion and slope instability. Arctic coastal areas in Svalbard and northwest Russia are often characterized by relative warm saline permafrost, fine grained marine silty and clayey sediments and a lack of rock outcrops and coarse materials. The continuous warming trend observed in Svalbard and northwest Russia since the 1980s are creating concerns related to the stability and durability of existing infrastructure on permafrost and uncertainties related to the design of new structures and infrastructure in the Arctic (Instanes and Anisimov, 2008). Coastal development in the European Arctic may, therefore, be vulnerable to future climate warming due to the predicted future increase in air temperatures and increased precipitation (Instanes et al., 2016) resulting in increased active layer thickness, accelerated permafrost warming and instability of the coastal bluff.

In this study, a methodology is suggested where the output from climate models is used as input to engineering models assessing change in the ground thermal regime at site specific locations in permafrost regions. The main objective is to determine the computed warmest ground temperature occurring during the service life time of the structure or engineering project, taking climate warming scenarios into

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consideration. The impact of future global warming on site specific coastal development can then be assessed.

An increase in ground temperatures may reduce the bearing capacity and increase settlement rates and subsidence of foundations, and cause instability of natural and engineered permafrost slopes. The sites in this study have been selected based on the current industrial development taking place in the region, availability of historical meteorological data, site specific data from statistical downscaling of General Circulation Models (GCMs), and soil and permafrost data from research sites connected to the SAMCoT research program in Svalbard and northwest Russia (see http://www.ntnu.edu/samcot). Based on an analysis of relevant data, the effect of predicted increased air temperatures on active layer thickness and permafrost temperatures has been evaluated. This type of information can be used in coupled thermo-dynamic and mechanical models of the local geotechnical site conditions including structural elements such as foundations, port structures, transportation systems and pipelines.

The first sections of the paper provide a summary of current permafrost engineering design, geotechnical site conditions and observed climate warming in Longyearbyen, Svalbard, and Mare-Sale, Baydaratskaya Bay, northwest Russia. Results from empirical-statistical downscaling of GCMs for the same sites are presented. The following section shows the impact on the ground temperature regime of the predicted climate warming, using data on permafrost and geotechnical conditions from the sites, and a simple transient thermo-dynamic model. The consequent impact on the stability of permafrost foundations and the coastal bluff is discussed.

2. Permafrost engineering design

Geotechnical design in Europe is based on the Eurocode, a standardized set of codes and regulations developed by the European Commission for Standardization (CEN, 2008; 2009). The main design philosophy in the Eurocode is that the structure should function according to the design assumptions during the service lifetime of the structure. Table 1 shows the design service lifetime for different structures based on Eurocode. It can be observed from the table that the Eurocode does not consider service life time longer than 100 years. For most buildings and common structures, a 50-year service lifetime or less is required. In permafrost regions the design service life time is in general shorter than the general requirement in Eurocode, due to the creep effect in ice-rich foundation soils. For example, in Canada, a 25-year design service life is common for ad-freeze piles in permafrost (Canadian Standards Association, 2010). In Svalbard, a 30-year design service life of foundations is standard engineering practice. Linear structures crossing permafrost terrain, such as pipelines, roads, railroads and runways, may require significant maintenance or special foundation design (for example artificial cooling devices, see (Canadian Standards Association, 2014; Instanes et al., 2016; Lepage and Doré, 2010)) to reach a service life time of 30 years without structural malfunction. For high-risk projects such as water retaining structures, tailings and storage facilities for hazardous waste, the environmental protection agencies may impose a design service life longer than 100 years for the structure (Instanes, 2012). The Eurocode emphasise the importance of defining and identifying relevant environmental design conditions at the design stage. This is, of course, especially important in permafrost regions, where the ground temperature regime governs the mechanical behaviour of the frozen soils and deformation and settlement of foundations (Andersland and Ladanyi, 2004). (Instanes, 2012) argues that the Eurocode should be the basis for geotechnical and foundation design also in regions outside the European Union, such as permafrost ground in Svalbard and northwest Russia. This is rationalised by the importance of the environmental aspects of the engineering design and the focus on specific geotechnical design considerations in the Eurocode. The Eurocode lists several geotechnical actions to be included in the geotechnical design, which are all relevant for frozen ground mechanics. This includes stresses in the ground, movements due to creeping, sliding or settling ground, and temperature effects including frost actions and ice loads. Especially important for permafrost engineering design are the effects of creep and temperature effects on the foundation soil behaviour.

Table 1
Design service lifetime of structures from CEN (2008).

Design working life category	Design service lifetime	Type of structures
1	10 years	Temporary structures
2	10 to 25 years	Replaceable structural parts for example gantry girders and bearings
3	15 to 30 years	Agricultural or similar structures
4	50 years	Buildings and other common structures
5	100 years	Monumental buildings or structures, bridges and other civil engineering structures

In the Eurocode, the consequence of failure or malfunction of the structure is handled through a reliability differentiation between three consequences classes (CEN, 2008) (Table 2). In addition, three corresponding reliability classes are defined which give a measure of the probability of failure or malfunction, through a minimum value of a reliability index (CEN, 2008). The reliability index can be considered equivalent to a maximum allowable annual probability of failure or malfunction (Instanes, 2012) (Table 2). The Eurocode states that the complexity of individual geotechnical projects shall be identified together with the associated risk (CEN, 2009). This is implemented by defining three Geotechnical Categories for different structures and soil conditions (CEN, 2009). Geotechnical Category 1 includes small and relative simple structures with negligible risk and allows for routine geotechnical design and construction methods. Geotechnical Category 2 includes conventional types of structures and foundations with no exceptional risks or difficult soil and loading conditions. Examples of geotechnical projects that fall into this category are: footings and slab foundations, piles, walls and retaining structures, excavations, bridge foundations, pillars, embankments and earthwork, anchors and tunnels. In all these cases, quantitative geotechnical data and analysis is considered appropriate, which includes routine field and laboratory work and routine geotechnical design and execution. Geotechnical Category 3 includes structures and soil conditions not covered by Geotechnical Categories 1 and 2. In Norway, Geotechnical Category 3 is, for example, mandatory for foundation design and civil engineering works in quick clay areas. According to (CEN, 2009), Geotechnical Category 3 includes very large or unusual structures, structures involving abnormal risks (such as quick clay), structures in highly seismic areas and structures in areas of probable site instability or persistent ground movements. Practical application of the Eurocode in geotechnical design in Norway is shown in Table 3 [based on Norwegian Public Roads Administration, 2014]. The table presents the minimum allowable partial factors to be used in deterministic geotechnical analysis. In frozen soil mechanics, dilatancy hardening effects are dominant in most cases (Andersland and Ladanyi, 2004). It can be observed from the table that for permafrost total stress analysis, assuming dilatancy hardening (neutral or dilatant failure mechanism), the minimum partial factor should be >1.4 to 1.5, depending on the consequence class/reliability class. The strength and deformation properties of frozen ground are temperature dependent. An increase in surface temperatures during the service life time of engineered structures on permafrost may cause increased active layer thickness and increased sub-zero permafrost temperatures at depth. This may reduce the bearing capacity of the supporting foundation soils, and increased creep induced settlements and subsidence of the foundation. In addition, increased active layer thickness may lead to slope instability and surface mass flow. This implies that the effect of climate warming in permafrost regions may cause unacceptable risk