Proceedings of the conference

AIC2018
Transportation Infrastructure Engineering in Cold Regions

May 1-3, 2018, Sisimiut, Greenland

ARCTIC TECHNOLOGY CENTRE

DTU

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Qeqqata Kommunia

Organised by:
Arctic Technology Centre, DTU Technical University of Denmark, May 2018

Arctic Technology Centre
Department of Civil Engineering
DTU, Technical University of Denmark
www.artek.gl
www.byg.dtu.dk

Editors : Thomas Ingeman-Nielsen, Daniel Pedersen, Ingrid Vernimmen

Byg Report R-388
ISBN=9788778774835

AIC2018:
Transportation Infrastructure Engineering in Cold Climates

Communities in the Arctic and other cold regions are strongly dependent on well-functioning transportation infrastructure to sustain business opportunities, health and general well-being. For isolated communities (most coastal Arctic communities) regional or international travel and transportation must rely on air or sea transport. The livelihood in other communities depend on low volume roads over challenging terrain. A harsh climate and unstable weather conditions affect constructions and make navigation challenging.

Faced with social and industrial changes, transportation infrastructure in these regions must be adapted to larger traffic loads and changing transportation patterns. At the same time, climate change impacts on permafrost and ground stability, sea ice distribution and properties, changing wave regimes etc., pose severe challenges to transportation infrastructure.

The ARTEK International Conference (AIC) in Sisimiut, Greenland is a recurrent highlight of dedication to research and developments on shifting topics of contemporary and future relevance for the Arctic societies. Since 2005, the ARTEK Event, now rebranded as *ARTEK International Conference*, have gathered researchers and engineers from around the world with expertise and interests in Arctic engineering and technology with the aim of sharing and assessing the state of knowledge and cooperating on joint efforts to push these ideas further. The AIC2018 offers an opportunity for participants from the science community, the industry, the public sector and other stakeholders to present, discuss and exchange ideas and experience on how to plan, design, construct, operate and maintain transportation infrastructure in cold regions.

The large number of high quality contributions submitted for the AIC2018 demonstrate a substantial interest in solving the challenges of transportation infrastructure in cold climates. With 40 oral presentations, 7 student pitch talks and posters, and more than 80 participants registered from most of the Arctic countries and beyond, the conference will offer rich opportunity for scientific discussion and networking, as well as cultural exchange and understanding.

It is our hope that the AIC2018 will contribute to the development of new exciting research and international collaboration across the Arctic, advancing the development of resilient infrastructure to support isolated communities in the Arctic and other cold regions.

On behalf of the organizing and scientific committees, welcome to AIC2018 in Sisimiut, Greenland!

Thomas Ingeman-Nielsen
Associate Professor
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PLANNING OF PHYSICAL INFRASTRUCTURE

Planning of Physical Infrastructure

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Introduction

An important characteristic of the climatic Arctic (10 ° C isotherm July) is a very small population base with scattered settlements, which are generally small and run like island operations and the fact that there are only a few larger cities. Even Greenland's capital Nuuk, is with its 17,000 inhabitants, on an international scale, a very small city.

The primary business is the exploitation and export of living or mineral natural resources, which are often exported relatively unprocessed, and increasingly tourism, where nature and culture are the primary attraction. Due to a weak and cost-intensive infrastructure, settlements only have a modest amount of non-natural resource-based production, and with the modest population base there is a weak basis for market-based competition, sectoral division and specialization. A large part of the Arctic settlements are dependent on economic transfers from the southernmost regions of the nation-state, unless the population lives in relative poverty, and the nature of the island operations means that the individual settlement is inextricably linked to its existence- and hence business base, as commuting on a daily basis is rarely possible. (Hendriksen 2013).

The very small population of the climatic Arctic, the scattered settlements and island operations inevitably leads to a modest and costly transport infrastructure, which is also challenged by the Arctic climate conditions with cold, strong storms and large areas of permafrost and periodic sea ice.

And with increased integration into the global world market, the need for stable and efficient transport infrastructure is rising - challenged by precisely the island operation and the Arctic climate (ibid.).

Using the geographical definition of the Arctic (north of the polar circle), these characteristics change somewhat. In the southern part, with the exception of Greenland, there is a better developed road network and coherent electricity grids, and in general, there are slightly more major cities. However, the basic characteristics with less settlements, island operation and limited opportunity for daily commuting are maintained.

Island operations societies' development dynamics

In the Arctic island operating society, development dynamics are governed by the interaction between the following three elements:

- The livelihood of the settlement. Primarily in the form of living and mineral resources for export as well as tourism.
- The population's capacity to exploit this livelihood.
- The extent to which the social infrastructure supports the utilization of the livelihood and the population's needs for connection to and trade with the outside world. (Ibid.)

The individual community is entirely dependent on the societal transport infrastructure in relation to food exports and tourism, as well as dependent on external supplies. At the same time, a relatively cheap and efficient passenger transport is the prerequisite for interpersonal relationships and a reasonable health service, including evacuations. For the raw material industry, it is often self-reliant in terms of exports because of its structure and the durability and quantity of the raw materials, but in terms of personnel transport and services, it will often be wholly or partly dependent on the societal transport infrastructure.

The Greenlandic example

With Greenland as an example, one of the major obstacles to a positive development dynamic for individual settlements is an inefficient and insufficient transport infrastructure, and one of the paradoxes is that the societal transport infrastructure is least developed in the districts currently having the best business development potentials - a bias that is historically conditioned.

Here, the Greenlandic island operation community is often challenged by a large degree of sectoralization of the overall societal infrastructure, where the individual sectors are forced into suboptimization, and the potential for co-operation and limited potentials for large-scale operations are not exploited optimally

(Hendriksen & Hoffmann 2017). At the same time, local competencies associated with arctic nature and other contexts are often not sufficiently utilized. (Hendriksen & Hoffmann 2016)

With Greenland as an example, this article discusses what criteria should be included in the planning of transport infrastructure in the Arctic island operation communities, where the goal is to support the development dynamics of each settlement. This implies prioritizing, based on the potential livelihood of the individual settlement. Furthermore, the extent to which financing of the necessary transport infrastructure can be supported by increased cross-sectoral cooperation is discussed.

Approach

The article is based on many years of research in the Greenlandic infrastructure and its significance for the development dynamics of the individual settlement and its potential for exploiting the local livelihood and business base - a research that has taken place throughout almost all of Greenland's 73 settlements (cities and villages). These are economic and demographic analysis combined with a range of qualitative interviews with local stakeholders and actors in relation to individual settlements as well as with national and municipal authorities and individual infrastructure companies.

Recently, in 2014, 2015, 2016 and 2017, the author conducted more than four months of extensive field studies of the total infrastructure in the northernmost district of the world with an original population, Qaanaaq with approx. 750 inhabitants. This has resulted in a systematic analysis of the challenges the very modest infrastructure entails for development dynamics, the opportunities for exploiting the potential local business base and the living conditions of the population (Hendriksen and Hoffmann 2016).

The focus of the article is the consequences of the Greenlandic sectorization and commercialization of transport infrastructure, based on a market economy approach without regard to the fact that the population base does not allow real competitive price formation. This has led to an incoherent transport infrastructure that does not take into account the regional nature and climate-related differences or the need for seasonal flexibility. A development that reflects inadequate planning and, secondly, that planning is not based on an analysis of the development potential of each settlement or district.

Conclusions

The prerequisite for increased sustainable economic growth in Greenland, and thus the possibility of independence, is a distributed and differentiated utilization of the country's geographically dispersed natural resources (The Committee for beneficial utilization of Greenland's natural resources 2014). This requires the construction of a transport infrastructure that, in its regularity and pricing structure, supports business development and the local population where the potentials are actually located – whether it is export of fish, shellfish and other foodstuffs, mineral extraction, tourism or .... Such infrastructure building requires systematic planning and prioritization based on a well-informed decision base, because there is a limited financial margin. In order to implement such planning and prioritization, it is necessary to carry out a nuanced analysis and mapping of both the current development dynamics of the individual settlements and their potential business development opportunities. Such an analysis is still unavailable.

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Permafrost Geotechnical Characterization and Mapping in Support of Climate Change Adaptation in Inuit Communities of Canada

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Introduction

The Inuit communities of Canada are remote villages widely scattered across the Inuit Nunangat (Inuit Country) that is composed of four territories: Inuvialuit, Nunavut, Nunavik and Nunatsiavut. With only one or two exceptions, all of them are located in permafrost zones and they are facing the challenge of adapting to changing permafrost conditions due to ground warming, permafrost thaw, drainage changes, landslides and thermo-erosion. Some large buildings and some houses in many communities have foundation problems, because of permafrost thaw caused by either climate change, faulty designs or lack of proper geotechnical pre-investigation. Damages to roads due to warming-induced thaw settlement occur in most communities. This difficult challenge of dealing with permafrost in transition occurs as there is a high need for new housing to accommodate a fast growing population and ease the social and health impacts of overcrowding in dwellings. Community services for those growing communities also calls for construction of large buildings such as municipal garages, town halls, elder's homes, schools and hospitals. Communities and hamlets that were decades ago small settlements around coastal trading posts and missions are now being modernized and are expanding.
The permafrost geotechnical characterization and mapping project aims at providing builders, communities and regional governments with the scientific support they need to adapt and develop on permafrost terrain. Indeed, this new urbanization calls for improved knowledge of permafrost conditions at a high spatial resolution (meter scale), informed land use planning, and acquisition by regional managers of the required understanding of permafrost temperature regime. One specific goal is to help select properly adapted foundations for different types and functions of buildings over variable permafrost terrain conditions.
Centre d'études nordiques (CEN) was involved since 2002 in assessing permafrost conditions in communities in Nunavik, starting with the particularly difficult case of Salluit where the fjord valley topography provides only limited space for construction and as the Quaternary glacial (till) and marine sediments are very ice rich. The spatial growth of Salluit was stalled for a decade after an active layer detachment slide in September 1998 prompted the abandonment of a new urban division project.
From that time on, an integrated, multi-technique, GIS-based, methodology for mapping permafrost conditions was developed and applied in 13 communities of Nunavik (Northern Quebec) and three communities in Nunavut. Beyond initial mapping, the approach also involves subsequent permafrost temperature monitoring and running predictive numerical models of permafrost temperature regime in the community's soil types according to climate change scenarios. In fact, knowledge of probable future permafrost rate of thawing is necessary to assume sustainability by making better choices of foundation designs for buildings and selecting engineering solutions for infrastructures.

Methodology

For each community, the mapping approach involves a number of steps:

1- Preliminary interpreting surficial geology on airphotos dating as far back in time as possible in order to be able to analyse landforms (e.g. frost boils, ice-wedge cracks, gelifluxion sheets, water tracks, etc.) indicative of soil types and ground ice content prior to perturbation by construction. This interpretation will be ultimately completed with recent remote sensing images. Survey points to be checked in the field and drilling sites are pre-selected at this stage.
2- Acquisition (by government means, ex. provincial or federal survey services or LiDAR images) or making (with DGPS and photogrammetry) of a high resolution Digital Elevation Model (DEM) of the community area.
3- Acquisition and consulting of previous studies (theses, consultant's reports, verbatim commentaries)
4- Field work, including:
   a. Local consultations with community members, Inuit knowledge acquisition and information sharing.
   b. Field surveys: active layer probing, including shallow soil pits, large pits dug with machinery, drilling with core extraction, destructive drilling with machinery to insert thermistor cable and to probe depth to bedrock, geophysical surveys (Ground penetrating radar and electrical resistivity), etc.

   c. GPS locating of local thaw settlements, deformed buildings, erosion features, small bedrock outcrops, as indicator of potential permafrost conditions.

5- Laboratory work: Sample analysis: ground ice contents (CT-Scan), water contents, salinity, grain-size analysis, Atterbergs limits, cell measurement of thaw consolidation ratios.
6- Information gathering and organizing:
   a. Defining the geocryological features (ice contents and structure) of permafrost in the various local surficial geological units.
   b. Compiling a georeferenced database.
   c. Advanced mapping of surficial geology.
7- Integrative mapping. Two types of derived maps are produced:
   a. A permafrost conditions map (based on grain size distribution in geological units and measured ice contents).
   b. A construction potential map
8- Presenting the research results and maps to the community for comments, explanations and answers to questions.

The construction potential map (step 7b above) is the end-result a multi-layer GIS-application that weighs and integrates the key terrain factors: slope angle (for stability issues), surficial geological material, permafrost ground-ice content, surface drainage and erosional landforms. It identifies:
1- terrains favourable for construction (suitable topography and little or no ice-content: green),
2- terrains that require further probing before making a final choice for a foundation types or that may be built with a specialized design (yellow),
3- terrains that should normally be avoided for construction (ice rich permafrost, slope angle permissive to slides, poorly drained, low bearing capacity: orange).

The map legend identifies for each map unit recommended foundation designs for different building functions and size (e.g. a municipal garage on slab on grade with thermosiphons or a small house on a pad and studs). All three maps (surficial geology, permafrost conditions and potential for construction) are provided to the community with an explanatory report and to the regional government (Kativik Regional Government, Nunavut Government) responsible for land use planning. Numerical maps and shape files are publicly available with all the georeferenced geotechnical data, pits and core locations and stratigraphic information.

Impacts of the characterization and mapping program

Using the maps and the geotechnical data, many communities have begun to avoid thaw sensitive soils and orient construction of new buildings on bedrock and on solid ground. The surficial geology maps are used mostly to provide land use planning orientation by providing a clear view of bedrock distribution and topography and of areas of shallow overburden where piles can be driven to bedrock at low cost. The maps on potential for construction are used as an information layer for designing community land use master plans along with other economic, social, architectural and public safety considerations. Through our participation in public audiences and community consultations, answers are given in person to technical questions that may arise in the planning process. A need that is now arising is to improve current spatial resolution in mapping depth to bedrock or coarse underlying sediments for anchoring piles.

As all the Inuit communities are located along coasts that emerged from the sea during the Holocene post-glacial marine regression (due to uplift), most of them have stretches of ice-rich silt and clay sediments that are thaw sensitive and where part of villages are already built. This creates a major concern with climate warming, particularly for southernmost communities near the southern edge of the permafrost zone where ground temperatures are nearing the thawing point. Monitoring permafrost thermal regime and modelling of permafrost temperatures for the next decades are therefore necessary to prepare for important decisions that lie ahead. More planning will be necessary and considerations will eventually have to be given to the increased use of foundations on piles rather than on studs and the probability of moving over time existing houses on better ground. We shall consider the engineering of steep bedrock outcrops to accommodate buildings.

CEN’s methodology also inspired similar work by other groups and partners in other Canadian territories such as Nunatsiavut and Yukon. High-resolution permafrost maps, georeferenced geotechnical information and predictive modelling have become indispensable tools for decision-making for the future of northern communities.

Remoteness and the Built Environment: On the Affordances of Transportation Infrastructure in Polar Regions

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Introduction

The polar regions, once largely dismissed as idyllic backwaters, have in recent years been transformed into a hotspot of economic and geopolitical interests (Schweitzer et al. 2017). Fueled by climate change, technological innovation and global resource depletion, the Arctic has become a site of grandiose development plans and of industrial megaprojects, while Antarctica continues in its role as an international arena for science infrastructure. These circumstances are attracting increasing attention from scholars of political economy and geopolitics. What is missing, however, is systematic study of the effects of polar infrastructure construction, maintenance and use on the people living and working in its vicinity, including both area residents and project workers.

Situating our research in the Arctic and Antarctic enables us to examine the concept of remoteness, which we primarily frame through its physical and spatial dimensions (extreme environmental conditions and distance), while acknowledging that it is a relative and relational term. The transportation infrastructures we investigate typically address remoteness by seeking to overcome it for the sake of distant interests. The aim of the project is to understand the affordances of infrastructure; that is, the opportunities and constraints emerging from interactions between people and infrastructure (Harvey et al. 2017). To meet this aim, we use comparative regional case studies that privilege the perspective of those who live and work close to selected infrastructures.

Given that infrastructures are at the center of this project, a definition is needed. While the notion of infrastructure can be used in varying degrees of inclusiveness, we define it narrowly in order to delimit and make manageable the proposed project. First, we take the prefix "infra" (meaning "under") seriously and focus on structures that underlay the operation of other systems. Second, in order to highlight the material dimensions of infrastructure, we focus on physical or "hard" infrastructure without excluding institutions and other "soft" forms of infrastructure from our research design. Finally, we focus specifically on transportation infrastructures, long-distance transmission systems that connect centers of population and commerce. The polar regions typically figure in these systems as providers of raw materials.

Approach

Our research design is radically proximal; that is, it builds upon the assumption that the human-infrastructural relations of those who live and work close to the infrastructures are most relevant, while at the same time we acknowledge that global, national and other trans-local connections and relations must also be taken into account. Thus, our methodology is multi-scalar, in social, spatial and temporal terms.

Affordance theory recognizes that what environments or objects offer to humans depends as much on the perceiver of these affordances as on the giver. This notion entered social science discourses via ecological psychology (Gibson 1979), and was further developed by design theory, sociology, and social media studies. Even closer to our research are works by anthropologists and archaeologists, which use the concept of affordances to highlight the relational properties of human-object relations. For infrastructure studies, this means that we need to pay particular attention to how specific groups of people perceive and engage with infrastructure objects. This includes vernacular affordances: latent, often unintended affordances discovered by users. This distinction between expert and vernacular leads to our usage of themes of skill, expertise, and engineering.

Our approach is decidedly ethnographic (Star 1999), that is participant observation and different kinds of interviews are part of our basic tool chest, while we also use variations of survey-based mapping and satellite data analysis. Observers pay particular attention to processes of material change. In the future, we plan to use infrastructure diaries, in which select "makers" and "users" document their interactions with infrastructure. Information from diaries, observations, and interviews, together with historical documents, maps, drawings, and other information, will become part of web-based infrastructure archives that will serve both as analytical tools and for dissemination purposes. These archives will have a dynamic access structure, meaning that sensitive information will be protected by passwords and other means.

Conclusions

Recent notions of the New Arctic and the "Technocratic Antarctic" (O'Reilly 2017) are indicators of the enormous outside interest that these polar regions are generating, and of the current and impending infrastructural build-up in both areas. Despite this brightening spotlight, actual social science research comparing and contrasting the Arctic and Antarctic is still extremely rare. Our project is intended to provide such an integrated polar comparison, while also producing systematic and detailed data on the local level.

Our approach is still in a conceptual and empirical testing phase. Thus, it is important for us to receive critical feedback from the field of engineering and neighboring specializations, in order to enable interdisciplinary conversations about transportation infrastructures in cold regions.

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Transport infrastructure and economic development

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Introduction

Infrastructure is one of the critical capacities (resources) in the Arctic and in Greenland. Infrastructure is core for a modernised and specialised society dependent on the mobility of people, goods, competences and information. In the Arctic infrastructures are costly and consequently transportation is a scarce and costly resource.

In Greenland the period of modernisation after WWII lead to the building of an extended infrastructure of harbours and in the local urbanised areas also over time a network of roads. This was not least the result of first military interest resulting in the building of airports followed by extended investments and technical achievements organised by the Greenland Technical Organisation. The result was a quite distributed network of transport operations able to connect and supply goods to most parts of Greenland.

In recent decades not least inspired by transport concepts and planning in much more densely populated and diversified economies in Europe and North America the means of transport has increasingly been organised within sectors and split into partly independent transport infrastructures and operators. This has been followed by recent challenges concerning the security of delivery and in diversified tariff structures and for many regions of Greenland rising cost for the users of the means of transportation.

The focus in this presentation and article will be on the economic and technical concepts and reasons for these changes in the employed transport regimes and the related governance and economic regimes. The question is how the geographic and distributed and highly specialised character of settlements, enterprises and economic activities is reflected in the choice of technical and institutional concepts employed in transportation. In addition, whether the governance and business models chosen are able to cope with the specific challenges of the cold regions of the Arctic and their specific conditions concerning climate, geography, natural resources and human activities and capabilities.

One of the big challenges to Greenland, but also to other regions in the Arctic, is the de facto limited investment capacity that can be motivated by the returns on investments that can be expected. In some few cases access to large deposits of minerals often located at distance from existing settlements may render specific transport investments feasible, but in many cases the development of new sources of income are very dependent on the utilisation of distributed natural, biological resources asking for semi-local improvements on e.g. land based infrastructures to make local production and the use of infrastructure nodes more efficient.

There seem to be rather obvious clashes between a neoliberal perspective on competition and sectorisation and the island economic conditions found in most of the Arctic reaching from Canada over Greenland to Siberia. A different pattern might be found in Northern Scandinavia not least due to the dominant welfare economic regimes and the resulting regional policy measures that can be found here. Still transport infrastructure in all these places are scarce, costly and critical for the economic activities and potentials for diversification found in the Arctic regions.

Approach

The analysis takes the starting point in the Transport Commissions report and recommendations for Greenland and the actions taken to implement some of these recommendations in the areas of transport by sea and by air.

The new business models and choice of technology and concepts of transportation employed by the shipping companies including Royal Arctic Line and in airborne transportation handled by Air Greenland. In the area of ship transportation, the enterprises have implemented new types of ships and new harbour installations have been built to accommodate the changed concepts of transportation. In the field of air transportation, radical changes in the transport infrastructure with new airport investments are planned. In both case huge investments are involved and the new business models are heavily dependent of changes in prices and tariffs as well as on international investments of capital.

To establish the grounding for comparing different transport concepts and infrastructures the specific climates, geographies, livelihood and natural resource potentials of the different region is an important input to the analysis. As a contribution, the local potentials will be analysed and options for local and regional transport infrastructures and scenarios presenting options and visions will added to complement and in some cases contrast the overarching transport plans for Greenland.

The choice of transport technology, business models, investment in ports and infrastructure nodes as well as the logistics implied in the overall concept of transportation are closely and critically interlinked. These interdependencies and the risks related to the capacity usage and investments payback time is analysed with respect to their economic, social and institutional sustainability. The methodology will combine heterogeneous models from economic cost-benefit and cost-effectiveness analysis as well as risk analysis concerning the social, regulatory and institutional aspects of the implementation of the plans and the capability to handle eventual consequences of concept flaws.

Conclusions

The analysis will highlight the risks related to the contemporary planning endeavours and ask for a more resilient and sustainable prioritisation of transport concepts and investments that supports the local economic potentials to utilise the natural resources available being the biological, mineral or the aesthetics of nature. Leaving these potentials as well as the needs of the distributed population out of the transport business models and concepts would be a crucial mistake and potential failed investment strategy for Greenland.

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The report from Transportkommissionens published 2011 complemented with a quite large number of reports and investigations presented by the commission. Development plans presented by the Greenland Municipalities. Contemporary technical reports about the construction of harbour, airports and the restructuring of the logistics and infrastructures.

Transnational extractive industry infrastructure in the Arctic: mega-systems serving local communities?

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Motivation

We will discuss whether mega-systems designed for bringing Arctic natural resources to global markets reach and serve local Arctic communities in sufficient and equitable ways to ensure local socio-economic development. The Arctic has for centuries been a source of natural resources for the international economy, which has created elaborate socio-technical mega-systems bringing natural resources to markets, which raises questions these mega-systems serve local Arctic communities.

Approach

The approach will be historical case studies:
The North Atlantic has been an integrated part of the European food system since the Middle Ages. During the 1900s, the Arctic has been a source of seafood, oil, gas, renewable energy and minerals for the world economy, and the Arctic remains a focus of attention for its natural resources. Examples of Arctic socio-technical mega-systems connecting local resources and global markets are, for example, sea-land-air delivery of seafood from the Barents Sea, North Atlantic or Bering Seas to markets, the North-Swedish mega-system of mining, towns (Kiruna), rail, energy, defense, Soviet industrialization of the Russian Arctic, or the Trans-Alaska Pipeline.

From a social and human sciences perspectives, these mega-systems always reflect the international political, economic and security system of the day. Today, the world and the Arctic is characterized by globalization and the rise of China and Asian economies. China and to less extent Japan and South Korea are large investors in especially Russian Arctic energy infrastructure.

Conclusions

Transnational infrastructure in the Arctic has historically and continues to be designed to bring Arctic natural resources to global markets. This infrastructure reflects the international political, economic and technological system at any given time.

Arctic local communities depend on this infrastructure also for other needs than bringing natural resources to global markets.

The extent to which Arctic local communities can influence such transnational mega systems to serve local needs depends on local human capital, local capacity and competence for decision-making, political participation, and political system.

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Technologies as mediators: People, materiality and nature in the composition of an Arctic expedition

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Motivation

The theme of this paper is the precariousness of technology. It focuses on its role as a mediator which brings about surprise and change in situations where not only technology but also people and nature make differences to the setting. This is where technology is less than a durable fact but more than a whimsical event.

This is important because technology can easily be seen as bringing durability to a setting. This is when life is uneventful (Latour, 1997) or processes are routinized and therefore tends to become an intermediary. In this capacity it facilitates the reproduction of social arrangements and tends to function as an input-out machine that provides a certain outcome by a specified input. This happens, for example, in a technological system such as the railroad through a jungle as described by Latour (1997) so that when persons take the train they commonly arrive at the destination. As Latour points out, without the train, the travellers would be required to create their own path "with a hatchet along a trail which is barely visible" (Latour, 1997, p. 175). Travellers in trains would see the journey as uneventful, while travellers on the ground would find events everywhere and always. The train would be an intermediator.

However, when the train fails, it is suddenly much clearer that it consists of many different and heterogeneous entities each of which mediates other entities. Or as Latour (1994, p. 47) reminds:
"How mediated, complicated, cautious, mannered, even baroque is the access to matter of any piece of technology! How many sciences – the functional equivalent of rites – are necessary to prepare artifacts for socialization! How many persons, crafts, and institutions must be in place for the enrolment of even one nonhuman!"

When technology falters it becomes clearer how many things it consists of; how many things interact to make it durable; how many things play roles. These things are not only material although many are, they are also people and whole systems of ideas such as the sciences. As soon as the train's smooth functioning is interrupted, travellers "would be back in the jungle we started with" (Latour, 1997, p. 175). If this happens, then technology is not an intermediary anymore; it is a mediator that conditions others to act as much as it is acted on by others.

The paper's research question is: how does technology perform when it is frail or at least not able to dominate the scenography enough to be a reproductive intermediator?

The difference between the two types of voyagers, following Latour (1997, p. 175), "comes from the number of others one has to take into account, and from the nature of those others". In particular, the others may be "well-aligned intermediaries, making no fuss and no history and lending themselves to a smooth passage" (the train), or, alternatively, they may perform as "full mediators defining paths and fates on their own terms" (the jungle) (Latour, 1997, p. 175).

When the old [hidden] connections get interrupted or challenged, an actor starts to impact on the relationships it is part of, whether it humans or nonhumans. And according to Latour (2005, p. 217):
"the more attachments it has, the more it exists. And the more mediators there are the better. […] Now it's the actor, which so far […] was kept as a point, an atom, or a source, that has to be flattened out and forced to take a star like shape".

The intended contribution of the paper is to generate theoretical sensitivities about technology in a way that parallels, yet extends, Czarniawska's (2013, p. 22) concern with organisation as standing in the way of organizing:
"… a common impulse is to build a structure—an organization—comprising existing networks. In most cases, however, this strategy misfires, and proves to be inferior to a spontaneous construction of an action net following the idea of what needs to be done. Thus, changing the focus of organization theory from organizations to organizing may not only refresh the theory, but also be of use to practitioners".

To study such a process, it is useful to mobilise a setting where technology is present but may not account for all its conditions. This would be a jungle but not quite with a stable train service. This would be a setting where many different types of human and material, or nonhuman, actors would be involved in bringing about effects.

Approach

The study's empirical setting is a 10-day expedition on dog-sledges, snow scooters and a motor towering vehicle ("motodog") in the Russian Arctic in February 2017. This setting involves technology such as snow scooters, motodog and dog sledges but it was not completely taken over by technology since nature such as temperature, ice and animals were all variable entities that continued to go into context with each other each mediating the effects of the others. This is a setting where both human-animal interactions and technically mediated interaction would co-produce the journey (Doré and Michalon, 2016).

To study this setting one of the researchers participated in the journey and made detailed observations of the process. The researcher talked to people, took part in the everyday chores of the expedition and had formal roles in relation to safety. Attention was paid to interaction between various people, technology and nature. The empirical material thus consists of mediations between various actors through role shifting, reorganizing of routines and reassembling of artefacts. Empirical materials cover several types of situations and responses to them by other actors.

Conclusions

In parallel, this study shows that technology is unruly in the sense that, more or less predictably, it sometimes is a mediator that bend the worlds around it. But in other situations it requires a lot of support from others to keep it in place. This shifting performativity happens because technologies mediate and are mediated by others including not only people but also importantly nature. It also happens because technology fails; it may be barred from progress by others such as nature and it may deteriorate by being used and thus requires the help of other actors both human and nonhuman including other technologies. Technology is therefore a conditional resource. As others have also noted, it is not so easy to keep a system in reproductive mode and this is because there is a dynamic to technology. It is not only disruptive as in innovation, but more importantly it is also used up or barred from playing roles, and then it fails to deliver its hopes and promises. Alternatively, it requires a lot of work of others to make up for its deficiencies.

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Transportation and the art of earning a living in Qaanaaq – a context oriented analysis of system challenges towards regional sustainable development

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Introduction

Today, as Greenland focuses on more economic and cultural autonomy, the continued development of societal infrastructure systems is vital. (The Committee for beneficial utilization of Greenland's natural resources 2014)

The challenges of supporting sustainable development in Greenland are considerable: The extreme and changing climate conditions, the diverse settlements in the huge and disparate geography and the on-going encounter between indigenous and modern cultures and practices.
Island operation is a special feature that highlights the need for and the challenges of transportation in between the districts as well as in between the settlements inside the individual districts. Island operations in Greenland are based on the fact, that with very few exceptions, there are no roads between settlements, and the overall transport infrastructure includes only ships, planes and helicopters for the regional trips, while local trips are depended on small dinkies, dog sledges, snowmobile and ATWs. (Hendriksen & Hoffmann 2017 a, b)

In this way, it is not possible to commute between various settlements on a daily basis and all settlements have to have its own power supply, watersupply and wastehandling. Furthermore, all settlements are dependent on their own social infrastructure such as a shop, school, church and healthcare (Hendriksen 2013). The island operation naturally creates great challenges in order to supply services to the citizens and the business activities. (ibid.)

Regional development and transportation in Qaanaaq

The potentials of Qaanaaq to support a new and more diverse way of earning a living by introducing fishing and production of dried fish (Qaleralik qullukkat /ræklinge) are closely connected to the development of a flexible and multimodal transportation of persons and fish and other resources inside and outside of the region. (Hendriksen & Hoffmann 2016)

Qaanaaq is Greenland's northernmost town with 640 inhabitants and one of the most isolated. Here halibut is caught only in the winter with long lines from the sea ice. While in the short open water season the traditional hunting of mammals is central. Traditional practises with the use kayaks and harpoons are maintained by the locals, which not only supports sustainable hunting but also constitutes a special resource for Inuit cultures and provides a potential for tourism. (ibid.)

At the same time, pressure is put on the transportation systems by a lack of financial resources and locally based professional competences as well as new market-based forms of organization. Against this background, the article discusses the challenges facing Greenland's Self Rule in relation to further develop the existing transportation systems and practises in order to contribute to the sustainable development of Greenland.

Hence, the key question of this paper is how to develop a transportation infrastructure to support the new businesses while at the same time upholding valuable existing local culture and practises. The paper pays special attention to the organisation of the infrastructure systems and points to the challenges of sectorisation and centralisation.

Approach – a qualitative analysis

The paper takes the outset of an extreme case of Qaanaaq and includes a historical analysis of the development of settlement and the transportation system. The transportation system is analysed in relation to the specific context with a special emphasis on potential business development and includes the interrelations with other infra structure systems.

The analysis is based on a mix of historical data, policy documents, statistics and qualitative case studies. Among other studies, the authors in 2014 and 2015 and in 2017 conducted more than three extensive one month long study trips to region of Qaanaaq to study how the local infrastructure supply and operation can be developed to support local sustainable development. Finally, data have been collected in relation to teaching at the Arctic Engineering Programme about arctic infrastructure, environment and planning since the programme was established in 2001.

Conclusions

The paper firstly concludes on the different forms of demands for a flexible and multi modal system for transportation in the region. Secondly, the paper points to challenges for developing the transport system in relation to the existing trends of centralisation and sectorisation that drain the district for knowledge and competences and furthermore are characterised with sub-optimisation. Finally the paper draw some recommendation on how to organise the national and region transportation systems in order to support regional sustainable development.

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Data and digitalization as a driver for a more coherent and transparent physical planning and sustainable development in Arctic

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Digitalization, geodata and democratic citizen involvement

Greenland is a large country with a very extensive geography and a relatively small population who live in cities and settlements scattered along the coast. Digitalisation can be seen as a means to modernize society and tie it closer together despite the large physical distances between the cities. The new National Strategy of Geodata 2018 – 2021 focus on how the potential in geodata and new digital solutions can be fulfilled. How can a more systematic use of basic data, new topographical maps and geodata become a tool for sustainable development and promote growth? The planning legislation in Greenland also stresses that the municipalities involve the citizens in a local dialogue and consultation in question and decisions about the future cityplanning. The difficult choices to be made along the way between short-term benefits and long-term sustainable development must be taken on a common understanding, and it is important that the local society can make their contribution to the discussions to be undertaken.

How can the Arctic cities with its remote settlement explore the possibilities in digitalization so that their citizens and stakeholders can take part in, contribute to and have ownership to the local development?

Infrastructure and accessability

The Arctic cities is typically situated quite remote from other cities and therefore is deeply demendent upon an efficient infrastructure (airport) that make the cities accessable to reach by airplane. Greenland existing infrastructure is largely defined by historic decisions that are not based on present and future challenges. It is therefore important that the planning and deciding of future infrastructure investment also have to support future development potential and not only historical and contemporary patterns. A better infrastructure can in some cases also pave the way for new business opportunities, particularly in tourism and mining areas.

But how do we know where to invest and what data are needed to point out new oppurtunities? On what ground can the Arctic communities and cities attract investments in infrastructure and thus increase productivity and competitiveness. And how can a reginal and national planning support a more balanced development? How do we work with global sustainable goals and indicators?

Climate changes

In the Arctic climate changes brings both new opportunities and new challenges. We are already experiencing new options in areas like agriculture and fisheries. New climate data (DMI) aims to analyze the consequences of climate change for selected sectors in Greenland and is distributed on the National geodataplatform NunaGIS.

How do we ensure that the planning, development and investment in the Arctic cities takes into account future climate changes so that we as a society address the negative effects but also ensure the utilization of the positive effects of climate change?

Demographic changes

Migration and urbanisation pose a real challenge for the cities in Greenland. As younger members of the population drift towards the more urban areas and larger cities rising old age ratios are putting pressure on the more rural and remote municipalities and smaller cities. At the same time, Regions are also struggling with gender balance with men out- numbering women everywhere but in urban areas. With a relatively small population of only around 56.000 people these demographic

changes pose a challenge not only to the migration in Greenland but also the migration of younger people leaving Greenland – and not coming back.

Can the Arctic cities and new investment in infrastructure somehow contribute to minimize the effects of migration? How can future planning of the arctic cities help to attract new citizens and make sure that the younger members of our society are coming back?

Character and identity of Arctic cities

The cities of Greenland has a certain character and identity that significantly differentiate the cities in Greenland form other cities around the world. This is also due to the fact that we don't have cadastre or private ownership to the land in Greenland. You cannot buy or sell land - only obtain an area-allotment. The space in-between building in the greenlandic cities is public and therefore it is often a very open cityplan where it is possible to move very freely around the cities from a to b. With the launch of the planning of several new airports in Greenland the Government of Greenland is very focused on creating the best opportunities for a growing tourisme industry in Greenland. As a travel destination Greenland can first and foremost offer some unique nature experiences - but also the meeting with Greenland's unique culture and cultural building heritage is something that impresses and can attract future tourists.

How can the Arctic cities keep their identity, essence and character and become even more liveable and attractive for both inhabitants as well as tourist?

HARBORS AND OFFSHORE CONSTRUCTIONS

Season development of Ice ridge consolidation, macroporosty and keel depth

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Introduction

Ice ridges are vital ice features and have important implications for engineering activities as well as climate models in icy waters. Three essential properties are the thickness of the consolidated layer, the macro-porosity of the underlying rubble and the keep depth. In the following a short review of the seasonal development of these are given.

Let us start by distinguishing between *First-year ice ridges* and *Old ice ridges*. First-year ice ridges do not survive the summer, whereas Old ridges is often split in between *Second-year* and *Multi-year* ridges that has somewhat different characteristics. We may define different temporal phase in the life of ridges:

1. Initial phase characterized by temperature gradients in the ice block and in between water and ice. The consolidated layer cannot be defined.
2. Main phase in which a refrozen and cold upper layer (=consolidated layer) can be defined either through temperature or through mechanical strength. The dominating heat transfer occurs from the bottom of the consolidated layer and up into the cold air. This causes a growth of the consolidated layer. The sea water below transfers some energy to the ridge keel and causes a decreasing keel depth
3. Decay phase where the ridge is heated both from below and from above. The water is often warmer than during the main phase (winter) so that the keel melts faster. The consolidated layer gets warmer, but its thickness is more or less constant even if the surrounding level ice is melting. There are now two options; either the ridge disintegrates completely or it survives the summer and becomes a second-year ridge. Second-year ridges are probably almost completely consolidated.

The thickness of the consolidated layer (h_c)

As stated above it can only be defined after the initial phase has ended, and it starts from a non-zero value. The consolidated layer grows faster than the surrounding level ice because it grow in the underlying rubble (unconsolidated layer) and not in water. The difference in growth rate is by the simplest model (Stefan's 1891) the square root of the rubble porosity (Leppäranta et al., 1995):

$$h_c^2(\mathrm{t}) = h_c^2(\mathrm{t}_0) + \frac{h_i^2(\mathrm{t}) - h_i^2(\mathrm{t}_0)}{\eta} \qquad (1)$$

where h_c and h_i are the thicknesses of the consolidated layer and the level ice, t and t_0 are the current and initial time and η the macro porosity.

This equation does not include thermal inertia and requires a comparison with level ice thickness. It applies during the main phase, or as long as the heat transfer up through the consolidated layer dominates. When the spring comes and the ridge enters its decay phase h_c will heat, but continue to grow as long as the temperature gradient close its bottom is negative. The underlying rubble provides an insulating layer preventing bottom ablation. The consolidated layer will more or less have a constant thickness even if the level ice is melting.

If the ridge survive the summer all (or most of) the rubble has melted, or collapsed and consolidated, so that the second-year ridge is more, or less completely consolidated. When the cold penetrates so deep that a negative temperature gradient reaches the ice-water interphase it will start growing again. Little information about these summer processes are available.

The macro-porosity of the rubble

The ratio of the non-sea ice material to the total volume gives the macro-porosity. The brine and air volume inside the pieces of solid ice constitutes the micro-porosity and do not contribute to the macro-porosity. Macro-porosity is usually estimated from 2" drilling through ridge keel. Any drop, or soft ice registered and the porosity is based on the accumulated length of drops (soft ice) divided by the total borehole length.

Most reported values of macro-porosity lies around 30-35%, but the measured values range from 10% to 45%, and we suggest that the large range is due to seasonal development where the macro-porosity decreases fast in the decay phase. Finally we should add that there may be considerable uncertainty in these values, as the method is person dependent.

The keel depth

The reaches its maximum at formation. Provided there is enough level ice and enough driving forces the keel thickness (h_k) may reach its maximum continue to grow vertically. Such a maximum thickness seems to depend on the thickness and strength of the level ice, thicker and stronger ice gives deeper keels (Tuhkuri, 2014). From formation the ridge keel is exposed to mechanical and thermal erosion from the ocean underneath and melting takes place. There is very little information of these melt-rates, but it is clear that ridge keel thickness decreases faster than surrounding level ice thickness, due to its porosity (and probably larger permeability) and the fact that it penetrates deeper into the underlying current. It is also clear that the water temperature is important, and few decimal degrees in water temperature causes substantial increased keel melting rates.

Correlations

From an engineering perspective the two parameters h_c and h_k give the first estimate the ridge action on marine structures, so that the correlation of these two parameters becomes important. The consolidated layer grows throughout the season and reaches it maximum in late spring or early summer, whereas the keel depth reaches its maximum just after formation and then decreases continuously. One should expect a negative correlation between when these two factor reaches their maximum. The keel ablation accelerates in the decays phase, so that the strongest negative correlation between these factors should not be included for the estimation of the maximum force on structures.

Conclusions

A review of the current knowledge of the seasonal development of three essential ridge parameters, the thickness of the consolidated layer, the macro-porosity and the keel depth is given.

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Acknowledgement

Thanks to my colleagues Anna Pustogvar, Aleksey Shestov, Evgenii Salganik, Åse Ervik, Aleksey Marchenko, Ilija Samardzija and others. In addition all UNIS/NTNU students who participated in field work, laboratory work and modelling, and with this created the content of this paper.

Statistics and Mechanics of Ice Loads on Inclined Structures: Results from Simulation-Based Studies

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Motivation

Arctic marine operations increase continuously due to the developments in Northern sea transportation, offshore drilling operations, and offshore wind energy. The Arctic is harsh, but sensitive environment, and it imposes stringent requirements for safety and efficiency of all operations. One key factor in developing safe Arctic operations is a reliable prediction of sea ice loads on structures. The ice loads are induced by a complex ice-structure interaction process (Figure 1).

The maximum ice load estimates require the use of statistics as the measured loads show wide scatter. Further, it is known that the ice rubble accumulation forming during the interaction process is one of the important factors affecting the ice loads. To understand the effect of the ice rubble accumulation on the interaction process, complex mechanics of the ice rubble must be accounted for. There are other important factors as well, but in brief, all estimates on ice loads should account for the statistics of, and the mechanics behind, the ice loads.

Aalto University ice mechanics group has used combined finite-discrete element method (FEM-DEM) to simulate ice-structure interaction processes. These simulations allow studies on long ice loading processes and their statistics, while accounting for the detailed behaviour of the ice rubble. In other words, they allow detailed studies that include both, mechanics and statistics, of the ice loads.

Approach

Figures 1a–f describe our 2D FEM-DEM simulations. In the simulations, an ice sheet of constant thickness was pushed against an inclined rigid structure. The modelled ice sheet consisted of rectangular discrete elements connected by Timoshenko beams and it failed at locations where the Timoshenko beams met a pre-defined failure criterion. The beams went through a cohesive softening process when they failed. Paavilainen et al. (2009, 2011) validated our simulation tool against data from laboratory and full-scale measurements.

In the study discussed here, we used six sets of 50 slightly perturbed simulations: parameterization for all simulations in a given set was the same, but the initial vertical velocity of the free end of the ice sheet was slightly varied. The initial perturbation caused different ice failure processes, which yielded different peak ice load values. The ice parameters varied between the sets were the ice thickness and plastic limit in contact (see Ranta 2018a for details and parameters of the simulations). We also used a set of 50 simulations with non-homogeneous ice sheet to study the effect of inhomogeneity of ice on peak loads.

Even if our study was simulation-based, we emphasize that the full-scale data on maximum ice load events is very valuable. It, however, has its limitations with the range of parameters being narrow, and in most cases, most of the ice properties being not well known. It is, thus, not easy to use the full-scale peak ice load data for careful statistical analysis. Simulations of ice-structure interaction process enable more straightforward approach, as in a simulation-based statistical ice load study, ice properties are known exactly and can be varied as wished.

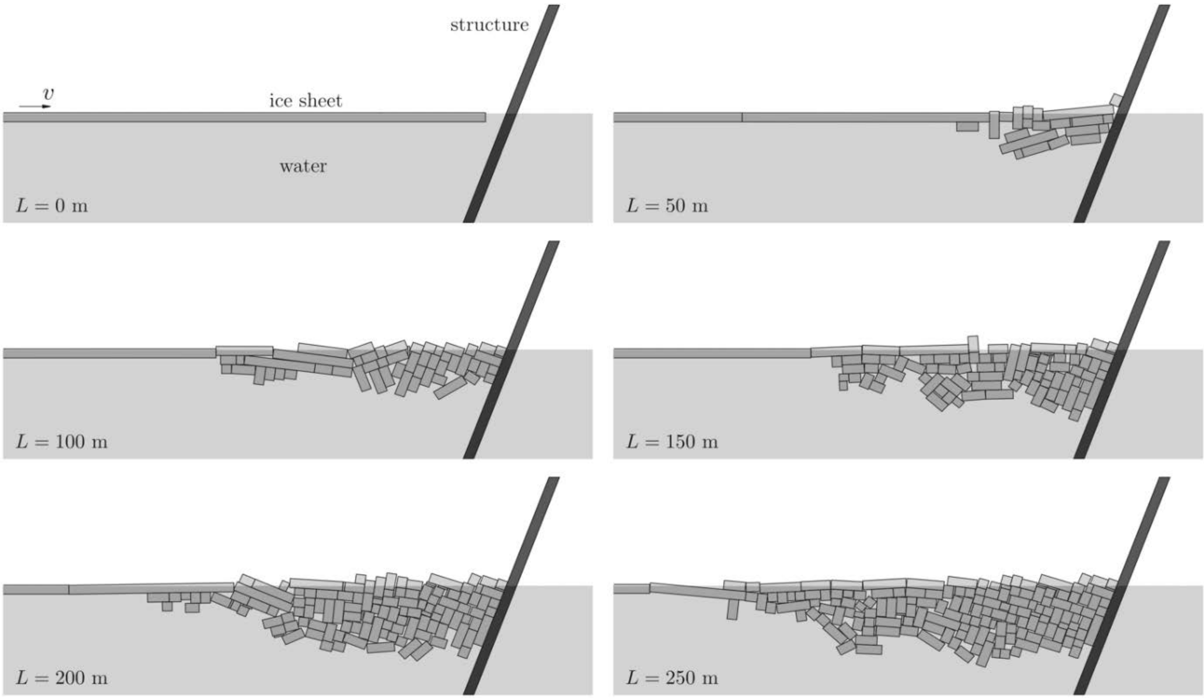

Figure 1. 2D FEM-DEM simulated ice-structure interaction process. An ice sheet moving with velocity v collides with an inclined structure. Ice rubble accumulation in the front of the structure increases in volume with the increasing length L of the ice moved against the structure.

Conclusions

The use of FEM-DEM has helped us to understand the statistics of ice loads and the behavior of ice in ice-structure interaction process. We used the simulations to produce sets of scattered peak ice load data, with the peak ice load values on the range of those measured in full-scale. We were able to show that the maximum ice load values only depend on very few ice parameters. Interestingly, our study also showed that the inhomogeneity of the ice may have the same effect on peak ice loads than the variation in the initial conditions of an ice loading process. In other words, the loading process may lead to stochastic peak ice load values regardless of the inhomogeneity of the ice.

The simulation data can be also used for the detailed mechanical analysis. Related to this, we have identified one important source for the stochastic peak ice loads: buckling of ice blocks belonging to the force chains (Paavilainen and Tuhkuri, 2013; Ranta, 2018b). The force chains are chain-like features consisting of a number of adjacent ice blocks under high compressive stress, and they transfer the load from the moving ice sheet onto the structure. Ranta (2018b) describes a simple buckling model, which is able to quantify the effect of the force chains. Our results demonstrate that the simulation-based research on ice loads, when subjected to careful analysis combining statistics and mechanics, brings new understanding on complex ice loading scenarios.

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Modelling of hydrodynamic and wave conditions for a new harbor in Søndre Strømfjord (Kangerlussuaq)

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Introduction

Søndre Strømfjord (Kangerlussuaq fjord) is located at the West coast of Greenland, Figure 1. There are three large river systems which transport glacial sediments into the fjord, i.e. the Watson River, Umivit River and Sarfartoq River. The Watson River enters the fjord at the North Eastern head and a well-developed delta is found at its outlet. The existing harbour in Kangerlussuaq is located at this outlet and experiences major sedimentation problems. Deposited sediments have reduced the water depth and hinders cruise- and large container ships from entering the harbour. In order to enter the port, small vessels transport passengers and cargo from the ships which are anchored further out in the fjord. The result is an inefficient operation and high maintenance cost for the municipality. Therefore, a new harbour location was proposed by Stenstad et al. (2015) 10 km further out the fjord near Hancock Pynt (HP), see Figure 1. The new location was selected based on seismic data and it was found that the onshore area is well suited for a harbour support area. The offshore sediments are mainly fine grained and not suitable as support for foundations. In addition, to reach the required water depth a significant amount of sediments need to be removed. The focus of this paper is to set up numerical models of the fjord system and provide the hydrodynamic, wind and wave conditions for the new proposed harbour location.

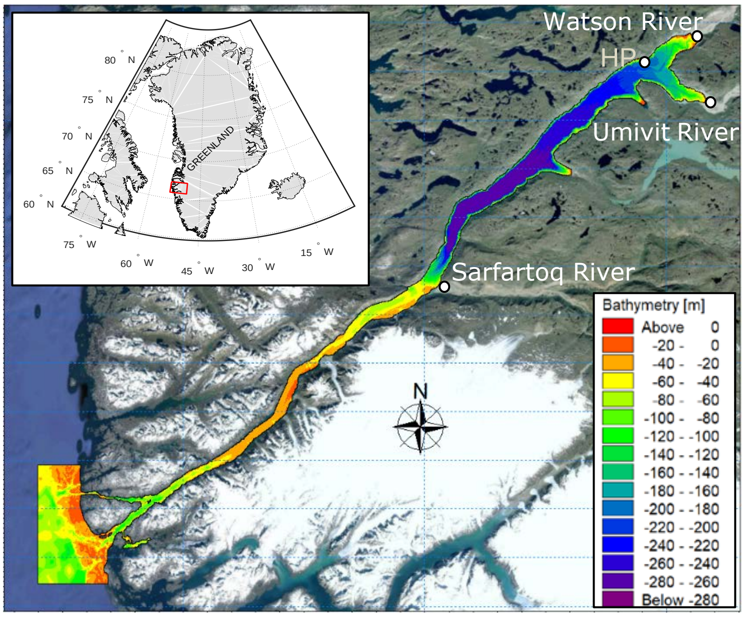

Figure 1. Top left figure is an overview map of Greenland showing the extent of the main map of Kangerlussuaq fjord. The bathymetry of the fjord is shown with a colour code which is also the model extent used in MIKE 21 FM. The new proposed harbour location Hancock Pynt (HP) and the three main rivers are indicated with white circles.

Regional Settings

Kangerlussuaq fjord is roughly 180 km long and has two distinct parts: the inner part which is broad (4-6 km) and deep (up to 280 m), and the shallow outer part which is roughly 100 km long, about 1 km wide and has a depth of 20-80 m. This shallow outer part is unusual for Arctic fjords because of its length and causes the water mass in the inner deep part of the fjord to be almost decoupled from the open ocean (Nielsen et al., 2010). The initial formation of ice in the inner part of the fjord system generally starts at the end of November. The sea ice expands all the way to the outer part of the fjord, close to Sarfartoq River, where the tidal currents are too strong for sea ice to form. In the inner part of the fjord, the sea ice reaches a thickness of about 1 m (Nielsen et al., 2010). An analysis of MODIS images show that at the end of May the last ice floats melt and open water is expected. The ice free period extents from the beginning of June till the end of November.

Approach

Two different numerical models were set up of the fjord system using the MIKE 21 software developed by DHI. The first numerical model is the MIKE 21 Flow Model hydrodynamic module. It simulates water level and flow variations by solving the depth-integrated incompressible Reynolds averaged Navier-Stokes equations (DHI, 2016). The fjord was surveyed by the Danish Geodata Agency in the summer of 2012 and the model bathymetry (Figure 1) was constructed from this data. The computational mesh has a resolution of 440 m outside the fjord and 300 m inside the fjord. There are three open boundaries located outside the fjord. The tides at these boundaries were predicted from a tidal constituents map constructed from the DTU global tide model (Cheng and Andersen, 2010). It includes 10 tidal constituents and has a resolution of 0.125 degrees. The model was calibrated against water level measurements which were collected in the summer of 2011 at multiple locations throughout the fjord. The main calibration parameter is the bed friction and the best fit was obtained by applying a varying Manning number depending on the water depth. The second numerical model is the MIKE 21 Spectral Wave (SW) module. It is a spectral-wind wave model and is able to simulate growth, decay and the transformation of wind-generated and swell waves. The model extent only covers the inner part of the fjord until Sarfartoq River. A computational mesh with resolution of 300 m was used and the model does not include any open boundaries. The wind input was obtained at Kangerlussuaq airport from 1976-2016 (Cappellen, 2017) and was adjusted for height and location. The model was calibrated against wave height measurements at a location close to Hancock Pynt for the period September-October 2013. The main calibration parameter was the type of air-sea interaction, i.e. how the momentum is transferred from the wind to the waves. The 'uncoupled' formulation, where the momentum transfer solely depends on the wind speed resulted in the best calibrated model. An extreme value analysis was performed on the wind data in order to find the wind speed with a return period of 50 years. This was done for two different sectors with the largest fetch, South-West and South-East. The obtained wind speed for each sector was used as input for the MIKE 21 SW model to find the corresponding wave height and peak period.

Results and conclusions

The hydrodynamic, wind and wave conditions found by analysing the wind data and from the numerical model simulations are summarised in Table 1. The tidal wave takes 3.5 hours to travel from the beginning of the fjord to Hancock Pynt. At Hanock Pynt there is a mean spring tidal range of about 3.5 meter and therefore it has a meso-tidal regime (mean spring tidal range between 2-4 meters). The tidal character can be determined from the four major tidal constituents which are at Hancock Pynt: K1 = 0.2575, O1 = 0.1252, M2 = 1.1935 and S2 = 0.3358. The form factor, F = (K1+1)/(M2+S2), is used to classify the tidal characteristics and has a value of 0.2503. Hence, the tide is mixed, mainly semidiurnal. The maximum flood current speed observed is 0.2 m/s and the maximum ebb current speed is 0.148 m/s. The 50 year return period wind speed, wave height and peak wave period for the South-West and South-East sector are shown in Table 1. It can be seen that the wave height coming in from the South-West is larger than the one coming in from the South-East. Though, the waves from both directions should be taken into account when designing the layout of the harbour. Beside the wind, current and wave conditions which are provided in this paper, further investigations regarding the ice forces and sediment transport are needed in order to come up with a suitable harbour design. Currently, a MIKE 3 model is under construction which will give a more detailed picture of the (3D) current field in the fjord.

Table 1. Wind, wave and hydrodynamic conditions at Hancock Pynt.

Parameter	Value	Unit
Lowest astronomical tide (LAT)	-1.74	m
Highest astronomical tide (HAT)	1.89	m
Maximum tidal current speed	0.2	m/s
50 year return period wind speed (South-West)	16.5	m/s
50 year return period wave height (South-West)	1.8	m
50 year return period peak wave period (South-West)	5	s
50 year return period wind speed (South-East)	16.1	m/s
50 year return period wave height (South-East)	1.18	m
50 year return period peak wave period (South-East)	3.95	s

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Consolidation of model-scale ice ridges: experiments, instrumentation and uncertainties

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Motivation

Ice ridges are formed from deformed ice under atmospheric cooling. In recent years, the part of deformed sea ice is increasing. Ridges are usually giving largest static loads on structures. At the same time, fieldwork studies with ice ridges are time-consuming and usually cannot provide data about ridge formation process, initial conditions before consolidation, and about potential full-scale loads on offshore structures and vessels. It literally means that almost all the parameters governing consolidation process are unknown or quite uncertain: initial macro-porosity η (volumetric liquid fraction), initial size, orientation, salinity and temperature of broken ice blocks forming the ridge, and snow thickness.

Scale basin tests can be used for the design of new structures. However, scale models of ice ridges also have disadvantages: complications with scaling down of ice microstructure, mechanical properties and performing natural ridge formation. Significant scaling of ice mechanical properties is possible only using dopants, which makes solidification process more complicated. According to Griewank and Notz (2013), the dopant concentration in growing ice depends strongly on an experimental scale and dopant density at different temperatures and concentrations. The research goal is to study ice ridge solidification in different scales to be able to predict its growth rate in basin and laboratory tests and to provide a better understanding of ridge thermodynamics in general.

Approach

Consolidation is mainly governed by ridge thermodynamics, so most amount of information can be received from thermistor strings. However, thermistors usually provide information about temperature distribution in one dimension while ridge consolidation is a multidimensional process. The temperature profile in the air above the ice is non-linear in the range of boundary layer. Ice surface temperature depends on the ratio between conduction in the ice and convection in the air, so it can be estimated from temperature gradient in ice and convectional heat transfer coefficient H_{ia} mainly depending on air velocity. The temperature profile in the ice during freezing is usually non-linear because some part of higher heat flux at the top surface is covering the amount of sensible heat to cool down the ice with growing thickness to transport heat. Additionally, ice thermal conductivity is temperature and salinity dependent. The temperature of water under the ice surface is usually slightly lower than bulk water temperature due to slow salt diffusion and salt drainage from the ice: the process when brine with higher salinity is substituting with water from the reservoir during ice growth.

According to Griewank and Notz (2013), sensible heat changes the ice growth insignificantly so in most cases linear temperature profile can be assumed. It is a weak assumption for fresh ice ridges and even weaker assumption for sea ice ridge, because during ridge solidification not only newly formed ice but also surrounding rubble should be cooled down to the equilibrium temperature profile. Temperature profile from voids can provide information about consolidated layer ice growth, while profiles from ice rubble can tell about the heat that is stored, extracted and conducted through it. The difference between these two profiles can show how strong heat fluxes in the horizontal direction are. Usually, the consolidated layer thickness h_c is assumed as the minimum thickness of newly formed ice after ridging process. The ratio of the consolidated layer and surrounding level ice thickness is called the degree of consolidation $R = h_c/h_i$.

In previous publications and engineering standards, ice ridges are usually assumed as a media with small pores evenly distributed in its volume. This simplification provides a simple one-dimensional solution of consolidation problem based on the amount of freezing degree-days and initial macro-porosity η where $h_c/h_i = 1/\sqrt{\eta}$. Coupling of conduction and convection in the air and additional sensible heat needed for rubble cooling can be implied to this solution (Adams et al., 1960) giving significant scale effect of level ice and consolidated layer growth rates (*Figure 1*). This solution is correct for small and mostly horizontally oriented blocks. Level ice h_i and consolidated layer h_c thicknesses can be found as:

$$h_{i,c} = \frac{2H_{ia}t\Delta T}{\rho L_{i,c}C_{i,c}\left(1+\sqrt{1+\frac{2H_{ia}{}^2 t\Delta T}{k\rho L_{i,c}C_{i,c}}}\right)}; \quad (1)$$

$$C_{i,c} = \frac{1}{2}\left(1+\sqrt{1+\frac{4}{3}\frac{c_p\Delta T}{L_{i,c}}\left(\left(\frac{H_{ia}h_{i,c}}{k}\right)^3 - 1\right)\Big/\left(\frac{H_{ia}h_{i,c}}{k}\right)^3}\right); \quad (2)$$

$$L_c = L_i\eta, \quad (3)$$

where t is the freezing time; ΔT is the difference between water freezing and air ambient temperatures; ρ is the ice density; L_i is the ice latent heat; k is the ice thermal conductivity, and c_p is the ice specific heat capacity.

A series of experiments with both fresh and saline ice was conducted to study the influence of rubble blocks scale, orientation and initial temperature on consolidation rate. Ice was cut into pieces with prescribed size, cooled down to the chosen temperature, placed into the water tank with side thermal insulation, and frozen under low-temperature laboratory conditions (-15°C).

The initial ice rubble temperature had a significant effect on model ridge consolidation with randomly oriented saline ice blocks: consolidated layer was up to 3 times thicker than surrounding level ice (Salganik et al., 2017). Consolidation of fresh ice ridges with only vertical and only inclined (by 30° from water level surface) blocks had almost no influence from rubble initial temperature and scale. During the initial stage, consolidated layer with vertically oriented blocks was growing as fast as surrounding level ice (Petrich et al., 2007), while during the main phase its thickness was close to the scale-independent solution for the thickness of $h_i/\sqrt{\eta}$. Consolidated layer with inclined blocks was growing close to the scale-dependent analytical solution from (1).

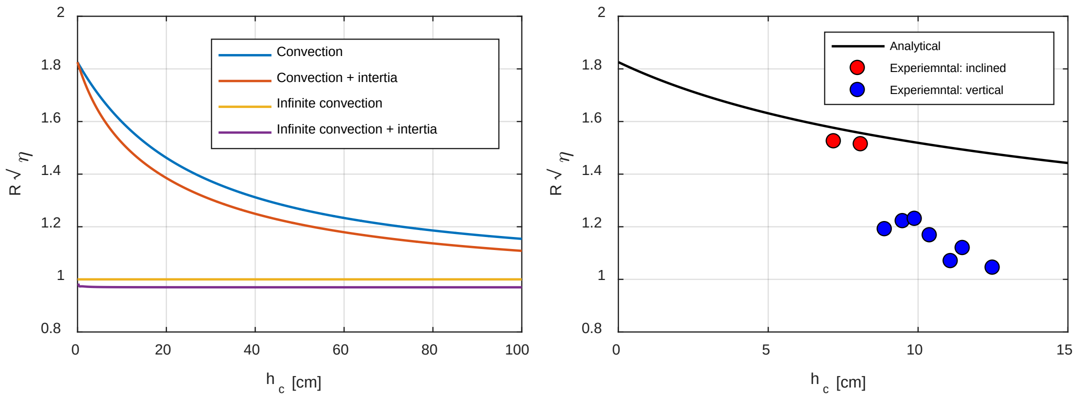

Figure 1: Ratio of consolidated layer and level ice thickness $R = h_c/h_i$ multiplied by the square route of porosity $\sqrt{\eta}$ vs consolidated layer thickness h_c for large scales and analytical solution (left) and for small-scale experimental and analytical values (right) for fresh ice.

Conclusions

Analytical solution for one-dimensional fresh ice ridge consolidation is provided showing the significantly faster growth of consolidated layer in comparison to surrounding level ice for smaller scales. Experiments were conducted showing that this scale effect is significantly stronger for slightly inclined than for vertically oriented ice blocks forming the model ridge.

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Probabilistic assessment of ice loads for an offshore structure

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Motivation

Designing an engineering structure is an act of finding the perfect balance of safety and economy, while fulfilling the requirements of structure's functionality. In modern design procedures limit state approach is used, which requires that the effect of combined factored actions shall not exceed the factored resistance. Guidance for implementing the limit state design are found in appropriate design standards.
ISO19906 standard provides guidelines for design methodologies for arctic and cold region offshore structures. It allows for deterministic or probabilistic calculation of representative values for ice actions, which are then used in action combinations with partial action factors to calculate the design actions for a specific limit state (e.g., ultimate limit state - ULS). Representative values are associated with a prescribed probability of exceedance. Therefore, probabilistic assessment of ice actions is the most appropriate approach for determining the representative values of ice actions. However, the required input data is often limited and that is why deterministic approach is acceptable as well.
Probabilistic assessment of ice loads requires a careful analysis of all aspects of ice-structure interactions, both from the points of view of the basic assumptions and of statistical interpretation. For purpose of this analysis the available long-term data, experimental and observational evidence, as well as the analytical findings are inadequate. The results obtainable at present, therefore, should be considered suggestive rather than conclusive. It is the insight in the nature of uncertainties and the essence of resulting statistical distribution of ice actions that is of immediate practical interest.
This paper shows an example of probabilistic assessment of ice ridge loads on an offshore structure.

Approach

Monte Carlo simulation is used in conjunction with deterministic formulae for calculating the ice ridge loads on vertical structure. For this case study, the Norströmsgrund lighthouse from Bay of Bothnia is chosen. It is a cylindrical structure with a 7.2 m diameter at the water line. The formulae for calculating the ice load are adopted from ISO19906. It is a simple approach where the loads from the consolidated layer and the keel rubble of the ice ridge are calculated separately. It is important to note that it is assumed that every ridge will fail against the structure. This is a conservative assumption, as some of the stronger ridges might not fail when there is not enough environmental forcing for full penetration of the ridge. Furthermore, it is assumed that both components of the load are peaking at the same time, which is also a conservative assumption. The total load, F_{tot}, is obtained by summing the two components.
Consolidated layer is considered to be failing in crushing failure mode and formulation for load calculation is the same as for the level ice load:

$$F_C = p_G \, w \, h \quad , \tag{1}$$

where w is the width of the contact area (lighthouse diameter), h is the average consolidated layer thickness and p_G is the average ice pressure over the nominal contact area and it is calculated as follows:

$$p_G = C_R \left(\frac{h}{h_1}\right)^n \left(\frac{w}{h}\right)^m \quad , \tag{2}$$

where C_R is the ice strength coefficient in megapascals, h_1 is the reference thickness of 1 m, m is an empirical coefficient equal to -0.16, n is an empirical coefficient, equal to -0.50+h/5 for h< 1.0 m, and - 0.30 for h≥1.0 m.
Keel rubble load calculation is based on approach used in soil mechanics for estimating the passive failure of granular material:

$$F_K = \mu \, h_k \, w \left(\frac{h_k \, \mu_\phi \, \gamma_e}{2} + 2c\right)\left(1 + \frac{h_k}{6w}\right) \quad , \tag{3}$$

$$\mu_\phi = \tan\left(45^\circ + \frac{\phi}{2}\right) \quad , \tag{4}$$

$$\gamma_e = (1-e)(\rho_w - \rho_i)\, g \quad , \tag{5}$$

where h_k is the keel rubble thickness, μ_ϕ is the passive pressure coefficient, ϕ is the rubble angle of internal friction, c is the apparent cohesion (average value over the keel rubble volume), γ_e is the effective buoyancy, e is the rubble macroporosity, ρ_w is the water density, ρ_i is the ice density and g is the gravity. To perform the Monte Carlo simulation, statistical distributions for different inputs and interaction rate (i.e., number of ridges hitting the structure and failing in crushing mode) needs to be defined. Considering season length, ice drift, ridge density (ridges/km) and percentage of them failing in crushing mode it is estimated that there are on average 1200 ridges failing against the structure during one winter season. Where the variation of a parameter is not significant, deterministic value is used (water density – 1005/m^3 and ice density – 910 kg/m^3). Where data is scare, uniform distribution with is used. These inputs are the rubble macroporosity (20 - 40%), the rubble apparent cohesion (5 – 7 kPa) and the rubble angle of internal friction (20° – 40°). The level ice thickness is simulated using a normal distribution for the maximum annual level ice with a mean of 0.72 m and a standard variation of 0.12 m (Leppäranta & Myrberg, 2009). For individual events, inner seasonal variations are considered. For a given season, maximum level ice thickness is sampled and the interaction events are randomly distributed in time throughout the season. To obtain the level ice thickness surrounding the ice ridge, average growth as described in Saloranta (2000) is considered (e.g., events early in the season will have smaller level ice thickness than those towards the end of the season). Consolidated layer thickness is then estimated by multiplying the surrounding level ice thickness with a factor. Here, this factor is randomly sampled using uniform distribution with bounds ranging from one to two. This reflects the fact that the ice ridges that have formed early in the season had enough time to consolidate and the younger ridges are only partly consolidated. Distribution (given an event) for the ice strength coefficient, C_R, is fitted so that in combination with the interaction rate, the annual distribution will correspond to the maximum annual distribution given in Kärnä and Masterson (2011). The used fitted distribution for ice strength coefficient was a gamma distribution with a shape parameter of 4.5 and a scale parameter of 0.09. The value of strength parameter is then reduced by 30 % from the value estimated for level ice to reflect the reduction in ice strength due to greater spatial inhomogeneity in thickness and strength of the consolidated layer. Keel depth is generally following an exponential type of distribution (Wadhams, 1983), and it is here simulated with a mean of 2.87 m and a cut-off value of 2 m.

Conclusions

Figure 1 presents the main results of the simulation. One of the interesting results is that the rubble component does not contribute significantly to the total load. This is because there is no correlation assumed between consolidated layer and rubble parameters. The probabilistic model described here can use different inputs for ice environment, so that a sensitivity analysis can be performed for a changing climate or different geographical locations. This study is the first step towards enhancing our understanding of how the uncertainties of ice data affect structural reliability of arctic offshore structures.

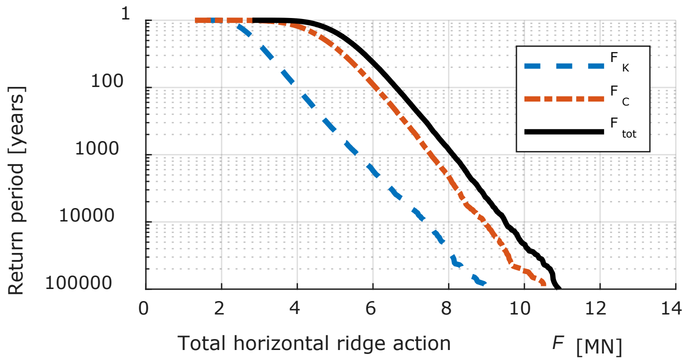

Figure 1. Simulated statistical distribution of the ice ridge loads. The blue dashed line is the rubble component, the red dash-dot line consolidated layer comonent and the black solid line is the total load.

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Numerical Modelling of Arctic Coastal Erosion due to Thermodenudation

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Motivation

Permafrost coastlines represent nearly 34% of the worldwide coastlines and they are exposed to increasing erosion rates, which endangers infrastructure such as roads and pipelines (Zetsche et al. 2005). The average coastal erosion rate in the Arctic is 0.5 m per year, and locally erosion rates up to 25 m per year are possible (Pearson 2015). Moreover, a further increase in coastal erosion rates in the Arctic is expected due to climate change. Warmer temperatures will lead to increased permafrost thawing depths during the summer months, which will reduce the bearing capacity of the permafrost and lead to settlements and bluff failures. The thawing of the permafrost will further accelerate the global warming, because approximately 25% of the global terrestrial carbon is stored in the permafrost and will be released when it thaws (Zetsche et al. 2005). Furthermore, warmer temperatures and a retreat of sea ice cover will result in an increase in human activities in the Arctic, e.g., new shipping routes can be developed or natural resources can be used. All this makes it important to develop reliable methods to predict coastal erosion in the Arctic and eventually to protect against it.

Coastal erosion processes in the Arctic are mainly of two types: thermoabrasion and thermodenudation. The earlier is caused by the erosive forces of waves and currents, which form a niche at the base of the bluff. When the overhanging material becomes too heavy and cannot be held by the shear or bending strength of the soil, it collapses. The thermoabrasion is highly periodical and leads to high and sudden coastal area losses. The thermodenudation, on the other hand, is thermally dominated and caused by the thawing and thereby the destabilization of the permafrost soil, which can lead to coastal slope failures. The thermodenudation is characterized by lower and consistent erosion rates and occurs mostly during calm weather conditions (Pearson 2015).

While there are already numerical models to simulate the thermoabrasion erosion process, simulating the thermodenudation process is still a challenge and no commercial software packages are currently available (Pearson 2015). This study provides a new approach to numerically model the thermodenudation erosion process using the geotechnical software Plaxis.

Approach

To describe the behaviour of frozen soil, Plaxis offers a user-defined soil model, i.e., the *Frozen and Unfrozen Soil Model* (Plaxis 2016). The model distinguishes between soil in frozen and unfrozen states. In the frozen state, the strength is described in terms of cryogenic suction and solid phase stress. The latter is formulated as the combined stress in solid particles of the soil and ice, whereas the cryogenic suction is defined as the pressure difference between ice and liquid water phases. Thereby it is possible to take into account the effects of ice and unfrozen water content as well as temperature variations. If the soil is present in an unfrozen condition, the Modified Cam Clay model is applied.

To assess coastal retreat rates using Plaxis, we need to perform safety analysis, i.e. slope stability analysis yielding global safety factors and possible failure planes. The conduct safety analysis, we need to determine and use the cohesion, the friction angle and the tensile strength of the soil as input parameters. Unfortunately, these parameters are not explicitly defined and readily available to read from the *Frozen and Unfrozen Soil* Model in Plaxis. Therefore, a new modelling approach was adopted here. The conventional Mohr Coulomb soil model was used to simulate the response of the unfrozen soil. For the frozen soil, a combination of the Mohr Coulomb soil model and cryogenic suction was used according to Eq. 1

$$\tau = c' + (\sigma' - u)tan\varphi'; \begin{cases} u \geq 0 & T \geq 0\,°C & pore\ pressure \\ u < 0 & T \geq 0\,°C & suction \\ u < 0 & T < 0\,°C & cryogenic\ suction \end{cases} \quad (1)$$

where τ is the shear strength, c' is the effective cohesion, σ' is the total normal stress, φ' is the effective friction angle, u represents the pore pressure, suction and cryogenic suction, and T is the temperature in

°C. The modelling approach was developed under the assumption that the slope failure leading to coastal retreat occurs in the unfrozen soil domain.

The newly developed thermodenudation model consists of two separate modules in Plaxis, which are coupled together using the open source Python language development environment Spyder. Figure 1 shows the main elements of the new model.

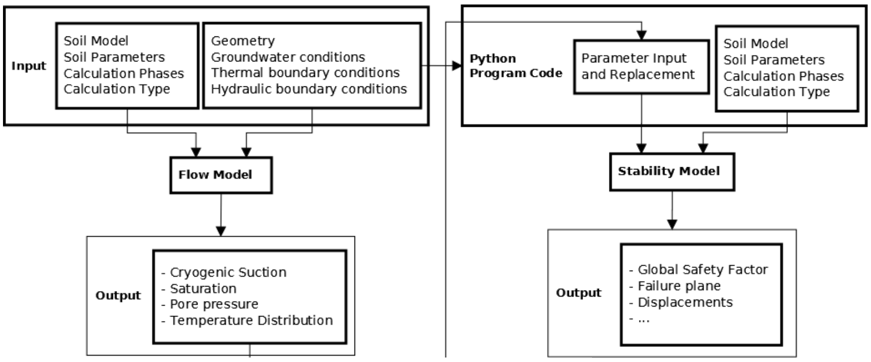

Figure 1: The thermodenudation Model set-up.

The *Flow Model* is used to define the geometry and the boundary conditions. In the *Flow Model*, the effects of freezing and thawing periods on the groundwater flow and pore-pressure are simulated. The *Stability Model*, on the other hand, simulates the mechanical responses and the slope stability of the soil due to the freezing and thawing cycles. The soil strength is described with the Mohr Coulomb model shown in Equation 1. The linear elastic perfectly plastic Mohr Coulomb model is computationally efficient, which leads to relatively fast computation of results.

Sample Results

The above model was calibrated and partly validated against full-scale data from Baydaratskaya Bay in Russia. Additionally, the effects of climate changes were studied by simulating the consequences of different climate scenarios predicted by the Intergovernmental Panel on Climate Change, IPCC (2001). Schnieder (2017) provides a comprehensive overview and a thorough discussion of the results. Table 1 presents a sample of the results related to the climate change effects on the study site.

	Bay. 2013	Baydaratskaya Bay 2050		Baydaratskaya Bay 2100	
	Reference	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Air temperature increase [°C]		+1.5	+2.0	+2.5	+6
Permafrost temperature increase [°C]		+1	+2	+1	+3
Active layer thickness [m]	0.88	1.24	1.28	1.51	1.90
Coastal retreat rate [m]	1.30	1.79	1.87	2.4	3.2
Potential eroded soil volume [m2/m]	44.46	52.49	56.56	60.87	69.48

Table 1: Results of the climate change scenarios.

Conclusions

The objective of this study was to numerically model the thermodenudation coastal erosion process. This was archived by adopting a new modelling approach in Plaxis. The model was successfully calibrated and partly validated against full-scale data from Baydaratskaya Bay in Russia. The same study site was also used to investigate the effects of the different climate change scenarios on the active layer thickness, the coastal retreat rates and the volume of eroded soil. The results of these investigations were quite consistent and showed a strong correlation between active layer thickness and coastal retreat rate.

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Multipurpose Berths in the Greenlandic Settlements

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Short description of the Abstract

The background for the need of new port solutions in the Greenlandic settlements is described alongside the challenges and a possible solution. The abstract is based upon the speaker's final paper made in collaboration with the Arctic Technology Centre, Department of Civil Engineering, Technical University of Denmark and Orbicon Arctic A/S, located in Nuuk, Greenland.

Introduction

Today the Greenlandic Government owns and maintains more than 160 port facilities in Greenland. Approximately 50% are located in the Greenlandic settlements while the remainder is located in the cities.
The ports are an essential part of the Greenlandic infrastructure and are often the only access to the remote settlements along the west and east coast. Besides being the gateway to Greenland the ports support the most important industries, fishing and tourism.
The construction of port facilities during the modernization back in the 60's and 70's was not subjected to any holistic co-ordinated planning which has resulted in a large and diverse port portfolio with regards to types of construction. The ports have since undergone little to no maintenance. Due to this fact some settlements have facilities that are obsolete and not up-to-date in relation to today's transport requirements. Meanwhile the outdated facilities exert an unnecessary economic burden which prevents possible developments in the sector.

Back in 2014 the Greenlandic Government initiated the composition of a sector plan regarding the Greenlandic port facilities[1]. The sector plan aims to develop Greenland's ports through a reduction in the number of facilities the Greenlandic Government own and maintain. The reduction is obtained by handing over facilities that are not deemed fit to be part of the future portfolio to other stakeholders and maritime-related businesses. Some constructions are in such poor condition that it is necessary to take down the facility.
Alongside a reduction of port facilities, the service commitments in the settlements held by the Government must remain in place through an update and standardization of selected ports. The demand for new and updated facilities are therefore required. Facilities that can serve and handle all the different patterns of use in the settlements.

The Multipurpose Berth Concept

The Multipurpose Berth seeks to solve the aims of the Port Sector Plan through a standardization of the port portfolio. This standardization of design and use of construction materials and methods will help secure the future of the port and harbour facilities without the use of extra resources.
A Multipurpose Berth should be able to serve all stakeholders and thereby be able to handle the Government's service commitments in the settlements. Commitments that range from universal service, transport logistic, passenger transport, maintenance of port facilities for the industries such as fishery, tourism and construction.
By a standardization of selected existing ports and future constructed ports the maintenance will be much more effective and thereby reduce cost and free up resources for further modernisation and renovation of existing facilities.

Challenges

But is it possible to develop and construct a standardized berth structure which can serve all demands while being implemented across the entire country where local physical conditions vary to a great extent?

The berth structures in Greenland must be designed to withstand the possible pressure from sea ice. At the same time, tidal differences in Greenland can exceed 5 meters (Nuuk area), which results in some existing berth structures standing on dry land at low tide. This is not at all beneficial for the transport logistics of goods to the settlements. Often supply ships have to wait for high tide or they have to initiate an ineffective barge operation to get supplies ashore. This takes time and the cost of transporting supplies increase.

The ice and tidal conditions result in the need of high and strong structures. At the same time, the berth structure must accommodate the loading exerted by the working hardware when handling goods and supplies on the berth.

Challenges related to the construction of new Multipurpose Berths in the Greenlandic settlements are mostly due to the remote location in which the constructions are built. Building materials and heavy equipment must be shipped to the remote location. Constructions is often carried out from the water side using barges and/or special vessels (See picture below).

Conclusion

Based upon the research done in the final paper, The Multipurpose Berth must to the extent possible require a water depth of 5 m LAT (based on the draft of the design ship). The berth must accommodate the placement of one twenty-foot container and be equipped with fenders, ladders, bollards, mooring rings etc.
The Multipurpose berth should be able to accommodate the placement of a tidal staircase for the safe handling of passengers at all tidal variations. At the same time, the berth should accommodate a pillar crane to the use of the local fishing fleet.

The above-mentioned requirements and specifications are best obtained through the construction of a solid sheet pile berth structure in front of existing berth structure. Thereby existing infrastructure is used and the cost is reduced. It is at the same time beneficial since the water depth normally increases when moving away from shore. If the water depth cannot be obtained in the immediate proximity it is possible to build the new berth structure further away from existing berth and connect the two by a bridge structure (See visualisation below). A possible bridge structure can be constructed in newer and lighter composite materials which easily can be shipped and handled in remote locations.

A Multipurpose Berth (80 m^2) connected to an existing berth by a composite bridge is estimated to cost approx. 4.500.000 DKK.

To the left: Construction of a duc d'albe in Kullorsuaq (JOEL, Orbicon Arctic).
To the right: Visualization of a Multipurpose Concept Berth (Simon Høgsholt)

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LINEAR INFRASTRUCTURE

Adaptation of the Saluit access Road in Nunavik, Québec

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Introduction

In the summer of 2012, rehabilitation and adaptation to climate change (CC) were undertaken to thermally and mechanically stabilize the airport access road which is a vital road link for the community of Salluit. Permafrost mitigation techniques used include the installation of a heat drain in the embankment shoulder on the downstream side of the road, construction of a gentle slope on the upstream side and improvement of the drainage system. The presentation will summarize research work done to develop and optimize the heat drain system, describe the rehabilitation and the instrumentation of the road, and present the results of a three-year monitoring program.

Development and installation of the heat drain

The heat drain is a permafrost protection method that activates heat extraction by inducing a convective air movement in a high permeability geocomposite membrane installed in the shoulder or across the entire backfill. Air ducts are installed at the base and the top of the drain to allow for free air circulation in the geocomposite (Doré and Beaulac, 2007). Ground heat is transferred by conduction to the drainage layer. The air in the drain gets warmer, inducing a convective upward air movement in the drain. As a result, warm air is expelled by chimneys at the top of the system while cold air is sucked into the drain through inlet chimneys (Jorgensen et al., 2008) (Figure 1).

Studies based on small-scale laboratory models and numerical models conducted at Laval University made it possible to establish the optimal geometry and size allowing for maximum heat drain effectiveness. Subsequently, large-scale field experimental projects carried out in collaboration with the Quebec Ministry of Transportation (Chataigner et al., 2009; Jorgensen et al., 2008; Ficheur, 2011) allowed documenting the feasibility of the installation of a heat drain system and verifying the effectiveness of the system in real operating conditions. Based on these research developments, it was concluded that the membrane must have a minimum thickness of 25 mm to maximize convective flow within the drain. It must include a low-slope portion to collect the heat from the ground, and steep section (1H: 1V) to induce upward air movement. A minimum embankment thickness of 1.5 m is required to induce significant convective motion in the heat drain. When properly designed and constructed, the drain has the capacity to cool down the bottom of the embankment by about 4°C in the winter and to raise the permafrost table by as much as 2 m.

The heat drain was installed in 900 m of the road embankment crossing a thaw sensitive permafrost area. The intent was to aggrade permafrost at the base of the embankment, reducing thus problems resulting from differential thaw settlements and allowing the formation of a "key" of frozen soils underneath the embankment to reduce the risk of slope failure in the sensitive area. In order to monitor the thermal and mechanical behavior of the embankment following the adaptation work carried out, thermistor cables (vertical and horizontal), inclinometers (vertical and horizontal) and a fiber optic cable (Distributed temperature sensing, DTS) have been installed in the embankment.

Thermal and mechanical performance of the embankment

Figure 2 shows the bottom of the active layer based on thermistor data in September of 2013 and 2014. The maximum thickness of the active layer is 3.3 m. Between 2013 and 2014, the thickness of the active layer shows a decrease 0.1 m to 0.4 m. The figure also shows that the permafrost is maintained approximately at the level of the embankment-ground contact beneath the heat drain. This seems to be a very good indication of the effectiveness of the heat drain since the active layer normally tends to thicken under the embankments slopes due to the heat retention caused by snow accumulation at this location in winter. Data collected using the DTS system also show that temperatures measured at the embankment-soil interface underneath the heat drain are lower than temperatures measured at the same location without heat drain.

Based on inclinometer data, despite the fact that permafrost aggradation has been observed at the site, lateral movement (embankment spreading) has been observed.

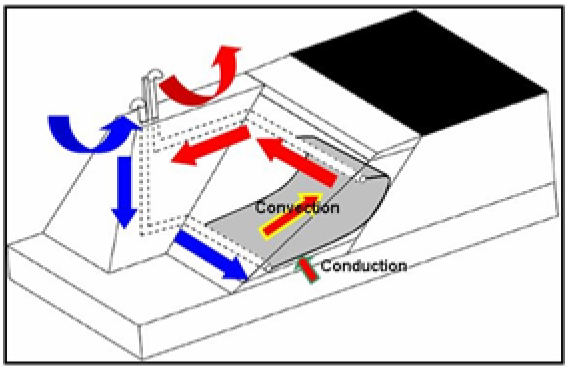

Figure 1: Schematic illustration of the heat drain

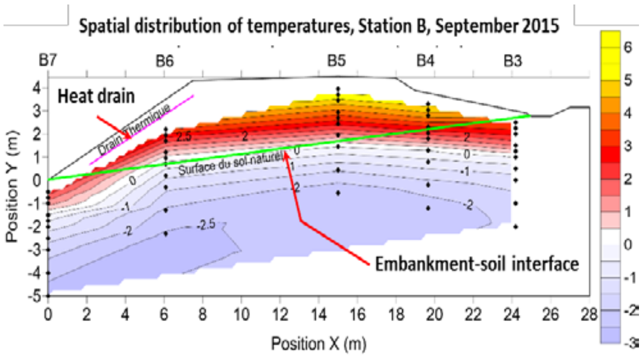

Figure 2: Thermal performance of the embankment

Conclusions

The Salluit full-scale application of the heat drain allowed to verify the feasibility and to validate the effectiveness of the system in a large-scale application project. Despite a few problems during installation including an error in the position of the drain in the embankment shoulder for about half of the project, the project is considered successful and the heat drain significantly improved the thermal conditions underneath the embankment. The gentle slope and the improvement of the drainage also helped improving the thermal behaviour of the embankment. Five years after construction, despite a constant lateral (spreading) movement of the embankment slope, the embankment surface is still very stable. The following conclusions can be drawn from the Salluit Road large-scale application project:

- The analysis of the thermal regimes indicates a rise in the permafrost table underneath the heat drain. In addition to this finding, several indices confirm the effectiveness of the heat drain including temperature data collected using the DTS and ice clogging of the horizontal inclinometers underneath the heat drain.
- Data collected using vertical inclinometers installed at the toe of the embankment slopes on the downhill side of the embankment indicate a significant lateral movement of the embankment despite permafrost aggradation of the permafrost underneath the embankment. The lateral movement might be caused by soil creeping or frost action in the active layer.
- The DTS system proved to be a very effective to monitor temperatures along the toe of the embankment and along the drainage systems. Warm spots can easily be detected allowing reacting with proper maintenance actions to prevent permafrost degradation.

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Frost protection of roads and railways: laboratory and field investigations

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Motivation

Norwegian road construction practice has changed considerably for the last 40 years due to the replacement of gravel by crushed rock materials in the granular layers of the pavements. The use of non-processed rock materials from blasting was allowed in the subbase layer until 2012. This was a reason for many problems with frost heaving due to inhomogeneity of this material, and in practice it was difficult to control the size of large stones. Since 2012 there is a requirement that rock materials for use in the subbase layer shall be crushed.

During the spring of 2014, Norwegian Public Roads Administration introduced a new version of handbook with requirements for roads construction in Norway, including new specifications for the frost protection layer. When pavements are constructed over moist and/or frost susceptible soils in cold and humid environments, the frost protection layer also becomes a very important part of the road system. According to new specification; the size of large stones for this layer should be maximum 0.5 m (longest edge) or ½ layer thickness, and minimum 30% of stones should be less than 90 mm. Fines content <0.063 mm) should be maximum 15% of the material less than 22.4 mm. The idea behind increasing the fines content is that well-graded crushed rock material can keep some humidity and provide resistance against frost penetration by increasing the latent heat of fusion. On the other hand, the fines content cannot be so high that the material becomes frost-susceptible. However, previous studies testing the samples of crushed rock aggregates from frost protection layer on the North of Norway demonstrated that it was no direct connection between fines and water content in granular layers.

"Frost Protection of Roads and Railways" is an international research project, supported by the Research Council of Norway (RCN), the Norwegian Public Roads Administration (NPRA) and Bane NOR (the Norwegian Railway Administration) (Kuznetsova et al., 2016). The project started in 2015 and was designed to tie together knowledge from cold regions engineering, thermodynamics, geology and mineralogy, and bring together researchers from Norway and Canada. The primary objective of this project is to build new knowledge on behavior of crushed rock materials and subgrade soils, used in road and railway construction, under cold climate conditions. In addition, the design methods for frost protection layer of roads and railways in Norway and other cold region countries will be improved. Since the large research program "Frost i Jord" ended about 40 years ago, very little research has been done in Norway on frost related problems in granular layers of roads and railways.

Approach

Field test site

During September 2016, a field test site has been built in Røros, central part of Norway, to have the results from real road and railway structures (Loranger et al., 2017). The road section is divided in 6 subsections (three – with crushed rock materials in the frost protection layer and three – with light weight aggregates) and a railway section, divided in 4 sub-sections (with using two different rock types and two different gradations for subbalast layer).

Three different gradation curves for three road subsections allows validating the effect of the material size on frost protection properties: A) coarse, B) fine, C) medium gradations. Three other subsections are built with use of Leca® and Glasopor®. Leca® material is an expanded clay round aggregate; Glasopor® material is cubical-like foam glass aggregate. Insulation is frequently used in Norway to prevent frost penetration in transport infrastructures.

Primary the use of light weight aggregates in the frost protection layer was not included into the proposal for FROST project, but it was necessary in order to get a full picture for evaluation of the changes in the Handbook N200.

Laboratory set up

In laboratory, three kinds of tests have been conducted: (1) small-scale (Rieksts et al. 2017a) and (2) large-scale experiments to measure heat transfer properties (convection, radiation and conduction) for different gradation curves (Rieksts et al., 2017b), and (3) frost heave test to measure segregation potential of granular materials.

(1) Small scale experiments focus on thermal conductivity of crushed aggregates and assess the effect of various mineralogies. Measurements are done using a steady state test method. Test sample comprises of test material compacted into cylindrically shaped PVC mold with inner diameter of 100 mm and height of 75 mm. Test sample is placed between two 25.4 mm thick borosilicate glass discs (Borofloat®) with thermocouples embedded in the center of the flat surfaces. The particle size of granular material is up to 16 mm.
(2) The test setup for large scale experiment comprises of a thermally insulated box with the inner volume of 1 m^3, as adapted from previous studies from Côté et al. (2011) The walls are made of extruded polystyrene boards with the total thickness of 0.3 m (k=0.03 W/mK). The box is equipped with two independent heat exchange plates that are placed below and on top of the sample. The voids between the tubing are filled with fine sand to ensure sufficient thermal contact. The plates are attached to cryostat units that are able to provide desired temperature gradients between 7 and 20 °C/m. In the laboratory, tests were perfomed on both crushed rock and light weight aggregates (Glasopor® and Leca®). The particle size of granular material is up to 200 mm.
(3) The segregation potential of pavement subgrade materials is measured by freezing tests using step-freezing conditions, which simulate more closely the freezing conditions of pavement subgrade soils. Under these conditions, frost penetrates at the selected rate and tends to stabilize at a certain level in the soil. A multi-ring freezing cell developed by Laval University is used. The 18 rings, 150 mm diameter by 225 mm high cell allows to test soils and crushed rock material with diameter up to 30 mm. The frost susceptibility criteria is determined using the Quebec Ministry of Transport (MTQ) Standard LC 22-331: Determination of the segregation potential of a soil.

Conclusions

The project "Frost protection of roads and railways" is running since June 2015 and several activities have been established during this period. In the presentation, we will give the overview of temperature data for two winters (2016-2017 and 2017-2018). So far, the best performance is observed from the road sections with light weight aggregates in the frost protection layer. The fastest frost penetration rate was observed for railway sections.
Three main laboratory experimental set ups have a focus on heat exchange mechanisms and frost susceptibility of granular layers of roads and railways to test the performance of frost protection layer after introducing new regulations in 2014. Small-scale experiment allows testing thermal conductivity of crushed rock material with different mineralogy in frozen and unfrozen states. Large scale air convection tests provides good insight into intrinsic permeability of tested coarse materials. The tests results fit well with results from other preceding studies and compare well to predictions of existing permeability models. The frost heave test performed on crushed rock material with different fines content will give understanding of frost susceptibility of road's granular layers.
Data from laboratory and field experiments have been used for validating and calibrating numerical models permormed in COMSOL® and FlexPDE.

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Frost protection in roads using insulation materials

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Motivation

Between 1968 and 1976 the Norwegian research program "Frost i Jord" (*FiJ* 1976) developed a design basis and practical design principles for design of frost protection of structures founded on frost susceptible materials. The results from the "Frost i Jord" project is still relevant for the design of roads and railways today, but some update due to change in type of material used must be accounted for. Recently, due to some problems on newly constructed highways, the 2014 revision of the Norwegian road construction regulations (N200) introduced a "new" layer in the base of the pavement structure (*NPRA* 2014), namely the "lower frost protection layer" (LFPL). This lower layer is made of granular material located below the insulation layer. Material of class T2 (i.e. with some frost susceptibility due to some fines for keeping relatively high water content) should be used for the LFPL. The layer is meant to provide a "heat storage magazine" and thus give additional resistance to frost penetration into the subgrade in addition to the frost insulation. Alternatively, this layer is meant to replace part of the frost insulation layer of extruded polystyrene (XPS), lightweight expanded clay aggregates, foam glass or the lower part of a thick layer of standard subbase material (although the latter is not part of the regulations). According to the regulation, some fine content is allowed/required in the LFPL. Depending on the grain size distribution, up to 15% of particles can be of size of silt or below, typically 7 to 8 percent will be the actual case. Therefore, a degree of saturation, S_r, at 50% or higher could be accomplished in the LFPL, if a void ratio of 0.5 or less is assumed. However, extra care must be taken during construction to make sure the layer is homogenous both horizontally and vertically. This amount of water gives increased heat capacity and latent heat (i.e. it serves as an energy storage for the system), when compared to coarser and more uniform materials. However, it seems like the effect of this layer is exaggerated. This is also shown by previous and recent results from field trials (Gardermobanen, Røros). Therefore, thermal analyses for some different geometries were carried out in order to quantify the potential effect of the lower frost protection layer. This extended abstract gives an overview of the results from these analyses and discusses the potential role of this layer in terms of consequences on the thermal resistance of the system.

Approach

Different hypothetical cross sections of a highway, similar configuration to the Røros test site, are modelled in a 1D model, where the thickness of the lower frost protection layer (h) and the thickness of the frost insulation layer (z) are varied. The yearly average temperature on the top boundary is assumed to be 4 °C, while the surface *Freezing Index* (*FI*) is varying between 16492 h°C and 39357 h°C. The surface temperature is assumed to vary with a cosine function around the average temperature. The analyses are started in October with initial condition having a uniform temperature distribution equal to the yearly average temperature (considered as a conservative choice, i.e. an unusual cold summer before the winter). The thermal properties of the different layers are given in table 1, where the insulation layer is meant to represent clay aggregates or foam glass. For the water and ice, a heat capacity of C_w = 4200 J/(kg·K) and C_i = 2020 J/(kg·K) are used in the LFPL and subgrade (silt). In these two layers, the thermal properties are calculated from the mixture depending on the temperature dependent composition. The two "extremes", i.e. with no lower protection layer (h = 0) and with no insulation layer (z = 0), is also included in the calculations. The thermal analyses are carried out using a finite element calculation. At the bottom boundary, a constant temperature equal to the yearly mean temperature is used. In addition analyses not considering heat capacity (C = 0) and with lower degree of saturation (S_r = 30%) in the LFPL are also conducted. Only considering latent heat of fusion exaggerates the effect of the LFPL (when using the geometry described above). However, the results will be extremely sensitive to the distance to the lower boundary of the model, since the only other heat source is through the bottom boundary.

Results and discussion

The results of the analyses produce a diagram of the relationship between *FI* (at the surface) and necessary thicknesses of the different protection layers. Figure 1 gives the resulting contour plot of z vs *FI* with contours of h. The dots are results of the analyses using parameters from table 1. These points fit well to the curves reported in *FiJ* (1976), when scaling the insulation thickness with the heat conductivity used in the 1976 report. The results shows that typically 300 mm of LFPL can replace 150 mm of lightweight expanded clay aggregates/foamglass. The square marks in Figure 1 represents the analyses with $C = 0$. The effect of the LFPL is exaggerated. As an example, as seen both in the curves below and in N200, a *FI* of 20000 h°C, 300 mm of LFPL can replace about 500 mm of insulation layer, which seems unreasonable. Finally, when $z = 0$ ($C \neq 0$) the analyses shows, for *FI* of 25802 h°C, that 1.0 m of LFPL is neeeded and a *FI* of 39367 h°C results in 1.40 m of LFPL.

		Density	Heat capacity	Total conductivity	Solid heat capacity	Frozen conductivity	Unfrozen conductivity	Degree of saturation
mm		ρ [kg/m³]	C [J/(kg·K)]	λ [W/(m·K)]	C_s [J/(kg·K)]	λ_f [W/(m·K)]	λ_u [W/(m·K)]	S_r [%]
50	Asphalt	2050	920	1.52				
200	Base	1900	890	1.35				
800	Subbase	1850	890	1.10				
z	Insulation	500	1300	0.14				
h	LFPL	1900			890	1.53	1.42	50
→ tot 7.5 m	Subgrade (silt)	2066		2.17	874			100

Table 1. Layer properties

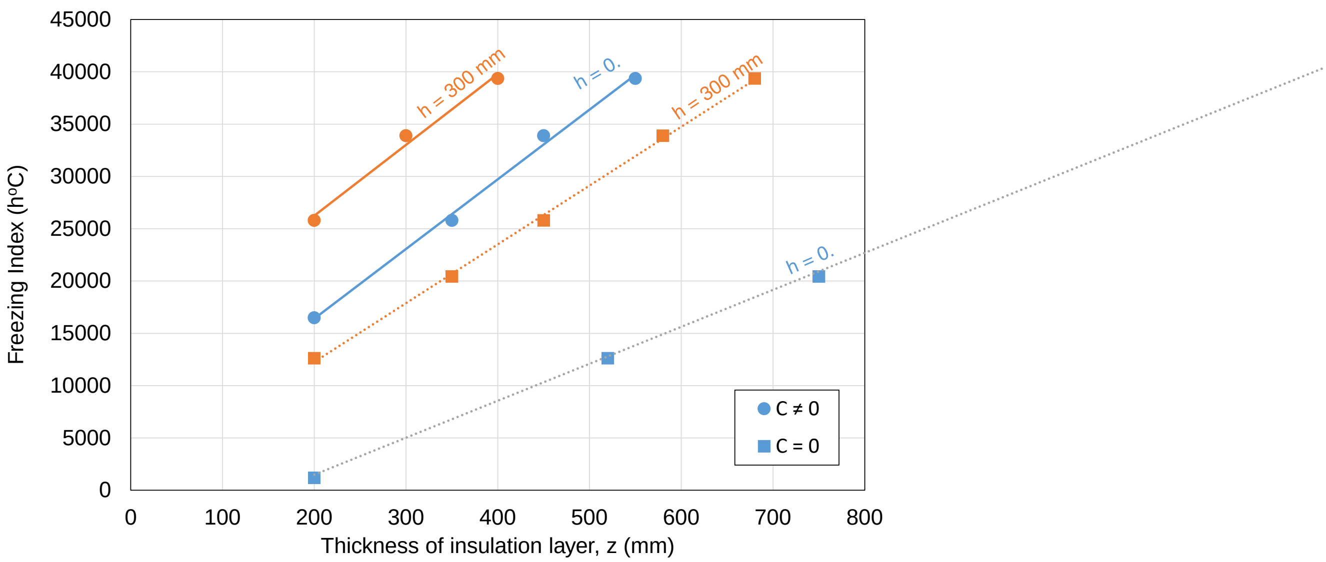

Figure 1. Thickness of insulation layer for different FI and thicknesses of the LFPL (h)

Conclusions and final comments

The presented analyses shows that the LFPL has a minor effect on thermal resistance compared to the gain in resistance by increasing the thickness of the insulation layer. Note that when using a LFPL, the results are highly dependent on the water content in the LFPL and the yearly temperature variation (order of varying winter periods and years). This means that if measures are not taken to acchieve the water content used in the analysis, the structure will be underdesigned. Also if one do not consider the whole lifetime of the structure in the analysis (but only a single extreme winter), one might risk that two cold winters in row with a cold summer in between essentailly keeps the LFPL frozen throughout and as a result the subgrade will freeze. To the authors, some extra thickness of the frost insulation layer seems like a tecnically and economically better solution than relying on a high water content and latent heat of fusion, risking a underdesigned or overprized structure. If the LFPL still is to be used, additional analyses for other yearly middle temperatures and time histories should be run in order to complete a set of curves that might be used for simplified design. This would require a thorough statistical analysis.

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Analysis of Frost Heave Data Collected at Minnesota Road Test Facility

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Motivation

Frost action is a major concern for pavements in cold climates. It may lead to the elevation change caused by the formation of ice lenses in underlying soil layers. Uniform heaving is not a concern because pavement stresses and strains due to the loading from this type of heaving are negligible. However, differential frost heaving may lead to pavement deterioration, such as roughness and cracking.

Although frost heave has been a subject of several theoretical, laboratory, and field investigations, the amount of field data concerning the magnitude of frost heave in pavements is still limited. One of the objectives of Minnesota Road Test research facility (MnROAD) was to fill this gap. MnROAD is a cold region pavement research facility outside of Albertville, MN constructed by MnDOT in 1993. It consists of the high volume [mainline] I-94 interstate highway section that carries interstate traffic and the Low Volume Roadway [LVR] that simulates rural roads. Thousands of sensors installed throughout the thickness of the pavement and operated by MnROAD personnel record load response and environmental data.

Approach

To evaluate the effects of frost heave, MnROAD personnel installed frost pins in twenty pavement test sections. Of these test sections, thirteen were mainline sections and seven were low volume sections. Eight of the sections were portland cement concrete (PCC) and the remaining twelve were hot mix asphalt (HMA). Each cell has 5 to 7 pins centered in each traffic lane, spaced about 15 m apart parallel to traffic. MnROAD personnel then used a rod and level survey equipment to accurately measure the elevation of the embedded frost pins with respect to a benchmark reference point over a four-year period. The pins were measured 75 times from November 1993 to February 1998. Most measurements were taken during the late winter and spring thaw seasons, from mid-February to the end of April. Pin information, locations, and elevation data were stored in a MnROAD database, totaling over 33,700 frost pin elevation data points.
An advantage of this dataset compared to frost heave data collected under similar studies was the quantity of data collected at a single testing location. The cells were in a very close proximity to one another, so all the cells essentially experienced the same weather conditions, had the similar soil composition, and were exposed to the same vehicle loading. The total thickness of the pavement sections (surface layer, base, and subbase) varied between 125 and 900 mm. It should be noted that according to thermal couple measurements, the depth of frost penetration at MnROAD in 1994 through 1997 varied between 1000 and 1250 mm. Therefore, every winter the maximum frost depth exceeded the total pavement thickness for all pavement sections.

The MnROAD frost pin elevation database was analyzed in this study. Change in pin elevation, CE, was first calculated for each measurement. The earliest day when each elevation measurement was available for all the frost pins was defined as a reference day. Then the CE value for a corresponding day of measurement was calculated as a difference between the frost pin elevation on a certain day and the corresponding frost pin elevation on the reference day. The CE for every pin was plotted as a function of time. Generally, every year CE starts to increase in the end of November and reaches its maximum around early March, after which it starts to decrease until approximately the middle of April. For most cells, there was no significant change in the pin elevation from May to November, and then it starts to increase again.
The magnitude of changes in the measured frost pins elevation was exceeding 75 mm on thin sections of the low volume loop and 35 mm on the interstate pavement sections. The differences in behaviour of adjacent pins (located 15 m apart) were also evaluated. It was found that frost heave was highly nonuniform with the difference changes in elevations calculated to be as high as 5 mm for the interstate sections and as high as 15 mm for low-volume test sections.

The effects of various major pavement design features on frost heave behavior were investigated in this study for both asphalt and concrete pavements. For each design feature, the analysis began with a visual and bivariate analysis where MnROAD cells were grouped in such a way that the groups would differ by a single design feature as best as possible. Further investigation of the interaction of design features within a design was statistically investigated by multivariate regression analysis and ANOVA testing on the selected data.

The effect of frost heave on ride quality was also investigated. No significant correlation between the measured frost heave and ride quality was observed, despite significantly non-uniform frost heave for some sections. It should be noted that the frost heave measurements were made only during the first five years of the pavement life. An evaluation of the subsequent roughness data found that the ride quality of the pavement sections with a higher degree of the frost heave non-uniformity deteriorated faster than that of the pavement sections with more uniform frost heave.

Conclusions

The results of the visual, bivariate and multivariate analyses show that subgrade and base type, pavement thickness and drainage capabilities are the major design factors that have the greatest effect on pavement frost heave separately and in combination. Sand subgrades heave less than clay subgrades. Thicker pavements heave less than thinner ones. Pavements with drainage capabilities heave less than those without. Permeable base drainage layers perform better than drainage structures. Fewer fines in base materials yield less heaving.

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Road bridges in Greenland, a survey

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Short abstract

What are the number and characteristics of road bridges in Greenland? Information on span, age, structural principle and construction material is collected using internet and other sources.

Figure 1. Bridge over the Ulkebugt in Sisimiut (left) and bridge over Watson River in Kangerlussuaq (right).

Abstract

Compared to other countries there are relatively few road bridges in Greenland. Since there are no roads between the settlements, the need of bridges is limited to crossings within the inhabited areas. The most common crossing for vehicles over small rivers or clefts within urban areas are dams with throughputs using Armco tubes or similar.
DASH7 airplanes superseded the Sikorsky helicopters for passenger air transport in the eighties and nineties and the landings at the airports changed from circular heliports to typically 800m long runways. The placement of the airports change from close to the city centre to 4-8 km outside the city. In Ilulissat and in Sisimiut it was necessary for the road to the airport to pass an inlet or a bay and the two cities got their road bridges, and the infrastructure change on the opposite side of the bay.

Settlement	Position	Opened for traffic	Span (meters)	Structural principle
Sisimiut	Ulkebugten	1998	2*75	Steel and concrete composite beeam
Thule	TAB North River	2002	60	Steel warren type truss
Kangerlussuaq	Watson River	ca 1950	ca 3*8	Steel Truss concrete plate
Ilulissat	Channel (Habour)	1984	60	Steel beams concrete plate
Maniitsoq	Harbour	1965	52	Steel arch
Qaqortoq	Harbour / River	2017	12	Fiber composite plate
Nuuk	New Harbour	?	?	

Table 1. Road bridges in Greenland with span larger than 10 meters (Preliminary list).

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NAVIGATION, POSITIONING AND COMMUNICATION SYSTEMS

Arctic Navigation, Positioning and Communication Systems for the Future

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Motivation and the state of yesterday

The transport infrastructure in the Arctic is challenges by the harsh climate and long distances between towns due to low population density, so transport is often based on air- or shipborne vehicles. To provide safe transportation it is of key importance to have access to accurate and reliable navigation, especial during approach and landing or docking.

The need for accurate and reliable navigation was addressed by the Federal Aviation Agency (FAA) in 1992 with the introduction of the Wide Area Augmentation System (WAAS) which supplements the Global Positioning System (GPS) in the United States. In 2003, the WAAS was expanded with Localizer Performance with Vertical guidance (LPV) capabilities. The LPV service provide functionality comparable with an airport Instrument Landing System (ILS) but without the need for expensive ground infrastructure. The LPV-200 service enable aircrafts to approach airports until 200 feet (~60.96 m) above the runway without the need for visual contact with the ground. In 2011 Europe introduced LPV-250 as part of European Geostationary Navigation Overlay Service (EGNOS) and later in 2015 it was upgraded to LPV-200. Lowering the decision height to 200 feet will decrease the number of landings delayed or cancelled due to low clouds.

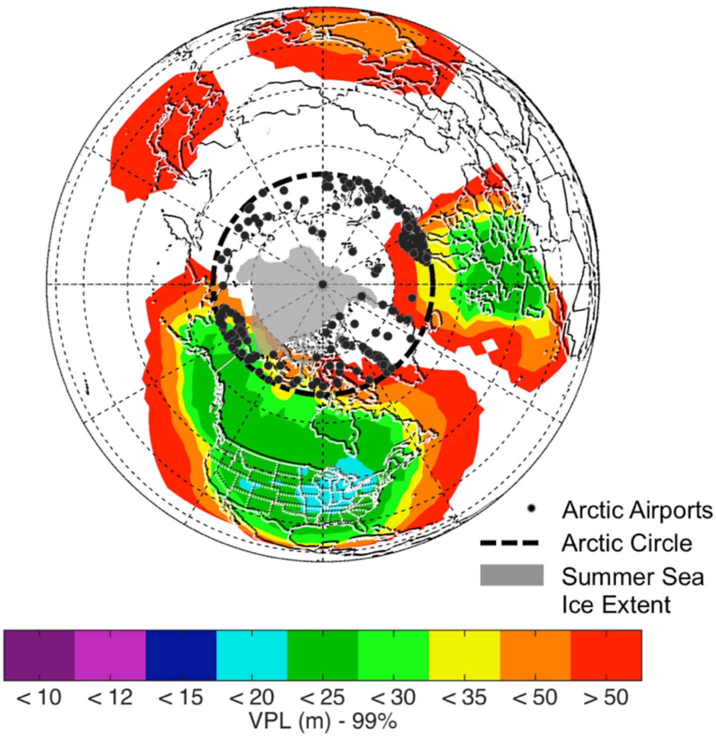

Figure 1: Vertical Protection Level (VPL) for single frequency GPS in 2015 using WAAS, EGNOS, MSAS, and GAGAN (from: Ried et al. 2016). VPL below 35 m is one of the criteria for achieving LPV-200.

Currently parts of the lower Arctic, i.e. Alaska, Canada, Sweden, Finland, and Norway (except Svalbard and Jan Mayen) are covered by Satellite Based Augmentation Systems (SBAS) capable of providing LPV-200 services. The SBAS services are being transmitted from geostationary satellites and are therefore generally not available above 72º latitude, furthermore the more dynamic ionosphere in the high Arctic is not modelled sufficiently in the current service algorithms.

Future possibilities

The Arctic Testbed is part of the European GNSS Evolution Programme in the European Space Agency (ESA) and investigates possible future enhancements for EGNOS (Kvam, 2016). One of the basic issues to address in the Arctic Testbed is the communication of the enhanced EGNOS signals to the users. The next issue that has been addressed in the Arctic Testbed is the more dynamic ionosphere in the Arctic.

To obtain the needed accuracy at high latitudes the Russian Globalnaya navigatsionnaya sputnikovaya Sistema (GLONASS) system has been included to provide more observations and improved satellite constellation since the GLONASS satellite orbit inclination reaches 64.8º where GPS only reaches 55º. Furthermore, additional reference stations in Greenland, Canada, Norway, Svalbard and Jan Mayen has been used together with the existing EGNOS reference stations. Finally, the benefit of estimating the ionospheric directly by using dual frequency GNSS receivers has been tested

Until now the Arctic Testbed have tested Iridium, the internet, and Automatic Identification System (AIS) with success. In addition to these communication satellites in quasi-zenith satellite orbit or near polar orbit currently being considered by Canada, Norway and Denmark could provide an attractive way of distributing the enhanced EGNOS signals north of 72º latitude.

Conclusions

The benefits of enhancing the SBAS systems in the Arctic are many and have the potential to improve safety, reduce travel time and energy consumption. The benefits can however only be achieved with continued investments in the needed geodetic and communication infrastructure in form of GNSS reference stations, maintained geodetic reference frames, reliable data connections to the reference stations, and communication means to distribute the augmentation data to the users.

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If the road could talk, what it would say to transportation?

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Abstract

This article will introduce service design tools in the context of smart road development for the arctic conditions. The development of these service design tools is related to Arctic Truck Platooning Challenge (ATPC) project. This is a research and development project related to developing transportation logistics and autonomous driving in in the arctic region. This project is funded with AIKO funding for regional innovations and experiments in Lapland, which is situated in the arctic Finland. The project is managed together with the Digipolis, University of Oulu and local transportation and logistics companies. This article is discussing on how smart road communication facilitates safe and more efficient heavy loads transportation in the arctic? And, other possible users? It is based on data, experiments, and service concept development in (ATPC) project

Service design tools

The Sinco is a laboratory at the university that enables fast prototyping in a digital environment. Necessarily it is not possible always to prototype in the real-life conditions or it is too expensive. Sinco through digital screens, sound, videos, and role-playing can take the prototypers in similar conditions that there would be in a real-life situation. The idea is to try, fail and learn very early, so no big investments are necessary. (Miettinen & Kuure 2013)

Service prototyping
Service prototyping can add value at various phases of the service design process and agile use of technologies to prototype customer journeys, service moments and different touchpoints quickly and iteratively. The use of existing technological solutions with mock-ups enables rapid visualization, concretization and evaluation of ideas. (Rontti et al. 2013)

Service design video
Service concepts and added value are best communicated through action and a moving image. A moving image concretises service moments and interactions. It can be easily distributed through new media channels. A service design movie, then, is a great way to develop and share your service concept and value offering within the business. (Tikkanen et. al. 2016)

Demo app
Using demo applications is a simple and practical way to communicate the ideas to the ones needing the application or to ones that are wanting to sell it to the final users. It is also one way of prototyping. Like the name says it is a demo, in other words a demonstration, what the real application could look and feel like. Testing it with the users can bring more knowledge how to develop it further. (Aktouf 2015)

The case

In autumn 2017 at an advanced service design course there was performed a case related to the transportation in the north with the Aiko funded ATPC project. The project began with benchmarking research first on the available technologies and making contacts with local institutions in the region. Strategic tools like ecosystem mapping and stakeholder mapping were used to identify the questions and areas of need to solve the problems with service design. We as team focused on how a smart road could talk and to whom. This problematic was found in more detail through interviews.

Also after making an Investigation of the current available road technology was it possible to know what to prototype. Sensor technology for example can tell the positions of the cars, animals, or other objects. Also, sensor vibration technology can tell the weather conditions of the road, which can bring a considerable contribution in timing truck platooning. The transporter can have more exact knowledge how long transportation of goods will take.

We used prototyping at the Sinco laboratory to understand and transmit the ideas. Making videos of the customer journey showed more service design areas what to continue to develop further. Role playing, when making the video also showed perspectives that had not been considered before making it. The video itself was a tool to discuss with the entities of the on-going of the project.

After prototyping/brainstorming we as a group came into a conclusion that a demo application of the services would serve the best to communicate about the activities on the road. The application dialogues, or shows road activities to the common users, but also the test drivers and the staff of the test driver entity of a smart road. Also there were considered how the road could talk with the truck platoons to make their trip safer. No longer need the drivers to make the work to inform for example about the animals or traffic jams, because the road does it automatically and people can read it in the application. The demo app also before hitting a traffic jam can calculate a new time efficient road alternative. It doesn't rely on users giving the feedback to the application, but on the sensor technology. It also has a possibility to add plenty of features to make the driving most time- and cost efficient and lessen the carbon dioxide emissions and share the drives in the future.

Findings and future studies

This article demonstrates the step-by-step use of these tools. The tools like rapid prototyping in Sinco, stakeholder mapping; and ecosystem mapping show how the groups were able to identify needs and use service to tackle these issues. They were also the basis to find the research topic itself. This case example demonstrates how service design can bring added value to the companies that apply it in their planning. It can make savings as the technology is applied smartly and in a user centred form. Co-working with the entities was central to make the demo application that enables a smarter transportation for example.

The paper suggests more future studies in autonomous transportation in the arctic region and how service design can contribute in it. Navigation in cold regions is a challenge due to the harsh climate. In future autonomous driving needs to face these issues. Snow and ice are one of the factors that are slowing down the coming of autonomous vehicles worldwide. Service design itself is a discipline that requires more networking with other areas like engineering in this case to treat better the challenges.

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Surface current mapping and ship route planning

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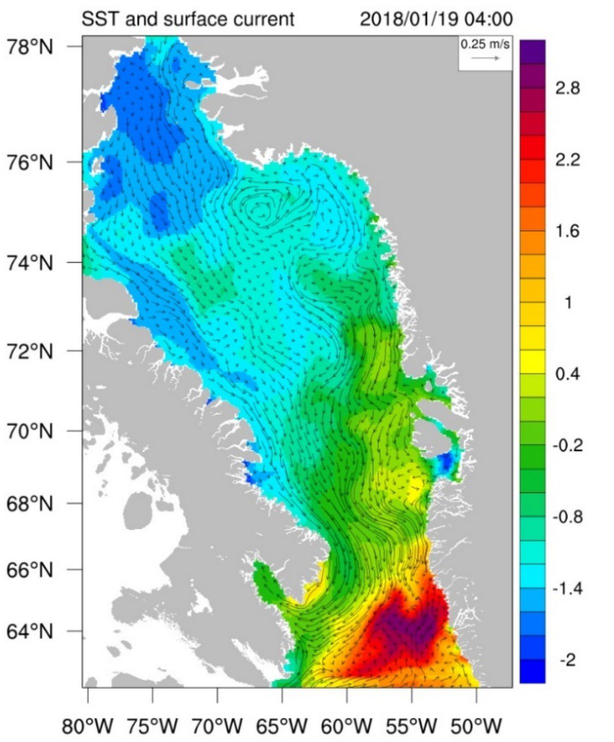
Motivation

The project "BlueSIROS" (where SIROS stands for Satellite Integrated Route Optimisation Service) is a collaboration between DTU Space, DTU Management Engineering, DHI and the Danish Defence Centre for Operational Oceanography (DCOO) and funded by the European Space Agency (ESA). The aim of the project is to study the feasibility of an operational system for marine route optimisation, which integrates modelling/forecasts of ocean currents based on near-real time satellite altimetry data.

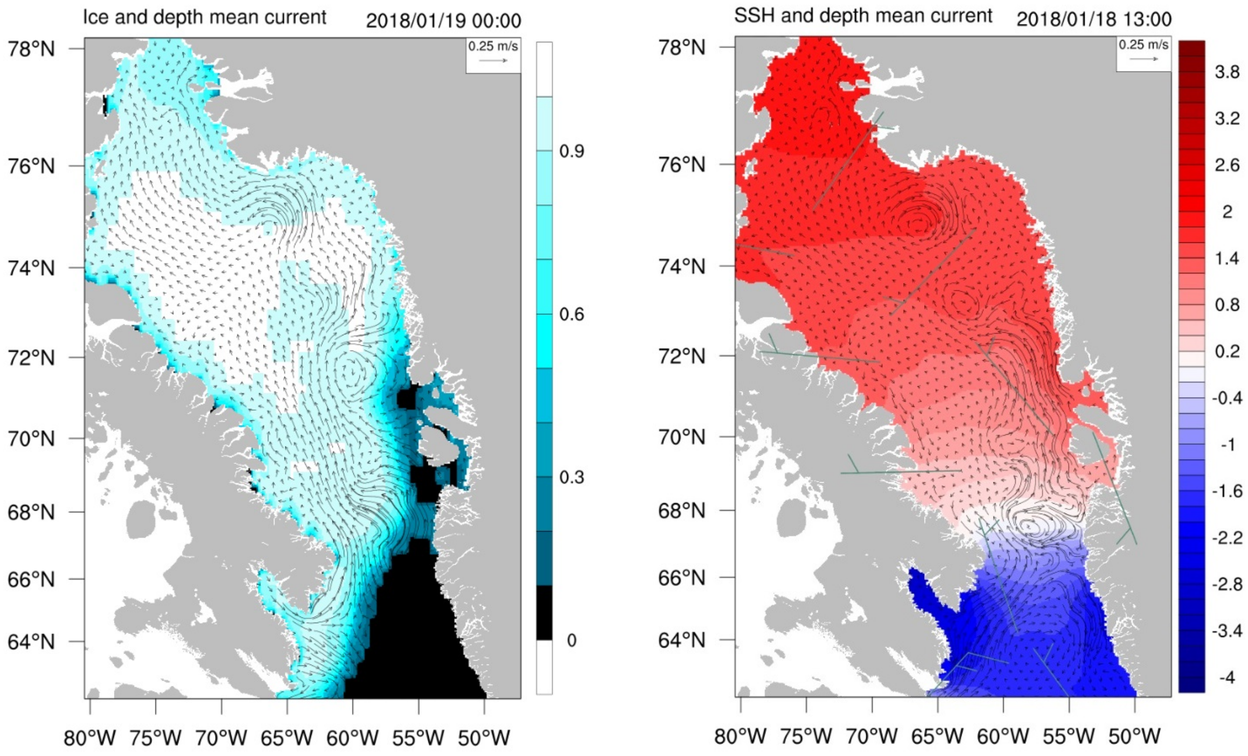
Approach

The operation of ships is affected by a number of environmental influences such as tides, currents, waves and winds. In most oceans there are regular currents that ships may be able to exploit for faster passage. Therefore, it is beneficial to take advantage of ocean currents when they are along the planned route, and to avoid the currents when they are in opposition. The North Atlantic, which is the geographic focus of this study, is probably the region with the most extensive use of ocean current information for ship routing.
The effects of dynamic currents have largely been neglected in earlier routing studies because, until recently, there has been no way to obtain reliable and timely estimates of dynamic current patterns. However, technological developments in satellite altimetry now offer the potential for providing accurate estimates of currents, wind speed, and wave height that can be used to improve ship routing. These data can be assimilated into an oceanographic model of current patterns or be used as direct estimates of current and wind velocities.
The aim of the study is to develop a framework for assimilating the real time satellite altimetry data into a route optimisation system enabling operators to minimize fuel consumption and reduce the fuel cost, thus increasing their profit. In addition, given that ship air emissions are related to fuel consumption, the proposed service minimizes the environmental impact of ship voyages and has a clear societal and environmental effect. By using weather routing vessels can also avoid dangerous weather thus reducing risks to personnel and the vessel. The ambition is to develop tools, which can simultaneously use vessel and Earth Observation (EO) information to predict optimal routing alternatives up to 10 days in advance with error estimates and with continuous near real time iterative updates ensuring the accuracy of the forecast.
Predicting ships' behaviour encountering wind, waves and currents via simulation models is even nowadays a great challenge for researchers. The most precise method to take into account the environmental influences is via detailed calculations of the ship's air and water resistance and seakeeping calculations. As a result, the ship is expected to realize significant time and fuel savings leading to improved scheduling even on some coastal voyages, whereas in the past, such savings were mainly realized on trans-ocean voyages. By using fine-resolution current estimates in portions of the Gulf Stream, average fuel savings of 7.5% when riding favourable currents and 4.5% when avoiding unfavourable currents are estimated for vessels with an average speed of 16 knots, which include most tankers, bulk carriers, and freighters.
The direct users of the route optimisation service will commercial vessels and shipping agents, who can benefit from a more accurate and fuel efficient planning and improved safety of the cargo and ship. This advantage of optimized route planning is for most companies critical for the reliability and efficiency of



Sea surface temperature and ocean surface currents for the Baffin Bay (ClimateLab).

logistics for harbour planning. With increasing ship traffic and fuel prizes there will be a natural demand for more efficient route optimisation systems in the future.
The proposed service will be a so-called "Near real time route optimisation service" as it will include the high-accuracy, high-reliability navigation capabilities provided by the GNSS system on board the vessel, feeding this information back to land using satellite communication to enable near real-time route re-optimisation and updating, which is then transmitted back to the vessel. This iterative update is similar to what already exists in navigation systems for cars on land, which has huge marked shares.



Sea ice cover and depth averaged currents below the ice (left) and sea surface height and depth averaged ocean currents (right) for the Baffin Bay (ClimateLab).

Conclusions

Route Optimisation is a growing market, and with the expected increase in maritime activity in the Arctic, it is vital that high latitudes will be included in future systems. Here the dependence on EO information will be even greater, as the general metocean data will be less accurate, and only the European Sentinels will be capable of providing EO information for marine route optimisation in the Arctic oceans.

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Does the Aerial Roof Marks on some Greenland buildings have something to do with navigation?

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Short description of the abstract

In a few Greenland settlements, you may see yellow painted marks on the roof of some buildings. The mark consist of a capital letter and a number, as shown on the three pictures below. What are the purpose of these marks?

Assaqutaq Narsaq Nuuk

Figure 1: Examples of Roof marking in three different towns/settlements.

Abstract

The answer to the question may be that the marks were meant to be an aid for flight navigation. Only few relevant sources are found. In a Regulation (1) from 1947 the Colony Managers were informed by the Government that the Aerial Identification Marks as known from the period of WW2 must be painted on one roof in each inhabited settlement. Letters have to be 3 m high and painted yellow on a black background. The marks consist of a letter A to L for the 10 colony districts in Western Greenland. Within each district, the settlements are given a number. The Holsteinsborg District (Sisimiut) got the letter E and the settlement Assaqutaq (former Kerrortussok) got the mark E8. Sisimiut city got E9 (the mark is no longer visible on the roof of the shipyard leader residence (B-14)). Letters and numbers were in increasing order from south to north.

The total number of marked buildings according to the regulation was 129. In a survey (2) in 1966 made by KGH (the Royal Greenland Trade Company) for information for Grønlandsfly (AirGreenland) the number is 83.

The use of the marks is most likely as navigation aid for the US Air Force aircrafts when crossing the Davis Strait on the flight from USA to British Isles in 1942-43. During Operation Bolero, a huge amount of aircrafts had to be transferred from US to England without crossing German occupied countries. With stops at the Canadian base at Goose Bay in Labrador, Narsarsuaq in Southern Greenland, Keflavik in Iceland the aircraft could fly from Presque Isle Army Airfield in Maine to Prestwick Airport in Scotland with no leg of the journey longer than 1370 km.

In a time without satellite based positioning, recognizable landmarks helped the navigator in the aircraft to establish the position. Approaching the Greenland West Coast the Aerial Roof Marks may have helped when the aircraft flew along the coast. Bluie West One (Narsarsuaq) is situated near A33 (Qassiarssuk). If you see a roof mark with letter B or later in the alphabet the aircraft is too far north and have to fly southwards.

In (3) Approach charts for Narsarsuaq show the settlements marked on the chart with the same mark e.g. A33, as mentioned in the regulation.

A flight navigation instruction stating this assumption on the purpose of the aerial marks has not yet been found.

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VESSEL AND BOAT TRAFFIC IN ICY WATERS

Sea Ice Loads on Ships

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Motivation

Arctic ships need to be designed and built in a way that ensures safe and sustainable operations in the harsh but fragile arctic environment. This requires understanding of the ice loads in different situations, but also understanding of the strength of the structures under ice loading. We will review our current knowledge on ice loads on ships and the strength of ship structures under ice loading. We will also highlight some future research needs.
The current trend in global warming changes the sea ice conditions and poses major challenges for arctic marine technology research. There are two important trends: (1) With ice conditions getting easier, shipping and marine operations extend into areas which were previously inaccessible, but in which the conditions will still be very harsh; (2) With summer periods getting longer, ships designed for open water conditions will enter areas with light ice conditions, e.g. oil tankers in the Baltic and passenger vessels in the North-West Passage. Both trends include major human and environmental risks: We do not know enough to ensure safe and sustainable operations in the Arctic.

Ice failure process, ice pressure

The ice load on a ship, or on a marine structure, is caused by contact and relative movement between the structure and ice. During contact an edge of the ice at first fails locally and the contact force increases until the force is large enough to fail the ice globally and the load decreases (Daley et al., 1998). After that a new loading cycle starts. Many different failure modes have been observed: An ice cover can fail, for example, locally through microcraking or flaking, and globally through bending, buckling or splitting. The failure mode is a function of indentation velocity, ice type, ice temperature, ice thickness, as well as inclination, width, shape, and compliance of the structure. Importantly, the ice failure process is not affected by the ice alone, but also by the structure, as well as the surrounding water. In order to understand ice loads on ships, we need to understand the ice-structure interaction process. Ice-structure interaction has been studied experimentally both in laboratories and in the field: Our current understanding is that the ice load is transmitted to a structure through small contact areas, aligned horisontally, with pressures as high as about 90 MPa (Riska, 1991). What are the important physical processes that lead to such a pressure distribution, is not yet fully understood.

Ice load on a ship

A measured ice load record on a ship hull appears random and consists of distinct peak load events varying spatially and in time (Suominen & Kujala, 2014, Suominen et al., 2017). A high scatter in these peak load values can be observed, but the parameters causing this scatter are not well known. The importance and variability of different ice properties is not well known, but there are also uncertainties related to the ice failure process, and even to the systems used to measure the ice loads. Recently, a stereo camera system has been developed to observe the thickness of the ice broken by a ship hull, and the ice failure process. This has been used to analyse the scatter of the measured ice load, and link the scatter to the prevailing ice conditions by applying statistical tools.

Strength of ship hull

The strength of ship side structures due to ice loading is an important design consideration. Similarly to other ships, also polar vessels are designed according to different rules and research efforts are important in development of the rules. A current important research topic is the response of grillage frames under a range of idealized rectangular (ice) pressure patches and different boundary conditions (Körgesaar et al., 2018). Finite element simulations have revealed that the patch length has a strong effect on the frame deformation mode. The key characteristic that differentiates the response under short and long patches is the longitudinal membrane stretching of the shell plating. Long patches tend to suppress this deformation mode and lead to similar frame behaviour as observed in isolated frame analysis; the strength of grillage frames reduces with increasing patch length to levels observed in isolated frame analysis. Analysis of plastic strain development in frames and in plating revealed that the plastic strain localises faster in frames, but shell plating is more sensitive to patch height variations.

Conclusions

The ice load on a ship is the result of a complicated failure process of the ice. Traditionally, ice-going ships have been designed by following experience from earlier ships. However, with Global Warming the ice conditions and ice properties are getting more variable, which is unfortunately increasing the risks in Arctic shipping and in other Arctic marine operations. With a changing environment, we cannot rely on historical data, but instead should desing ships based on first principles of mechanics. In order to do that, we need to study and understand failure processes of sea ice, physics of ice loads on ships, and the strength of ship structures. Currently we do not know enough to ensure safe operations in the Arctic.

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Knowledge gaps in studying wave-ice interaction

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Motivation

Sea-ice cover in the Arctic retreats appreciably as a result of the accelerating climate changes. This trend promotes an increase in the commercial activities in the Arctic, e.g., resource exploitation and sea transportation from Europe to the Far East. On the other hand, wave climate gets worse because of the presence of larger open water areas in the Arctic Ocean than ever before. Waves and ice interact with each other in a nonlinear coupled manner. Waves change ice floe sizes and thickness distribution both spatially and temporally. Ice is broken up because of wave-induced bending stresses and moved around by drifting and oscillating wave forces. As for waves, sea ice attenuates, scatters, reflects and refracts wave; and it changes the dispersion relation of waves. Wave-ice interactions research has a long history and can be traced back to 19th century. However, many underlying mechanisms are not well understood. It follows that modelling the wave-ice interaction still needs much research. In this study, we focus on marginal ice zone (MIZ), which is an interfacial area between open sea and interior pack ice. In MIZ, effects of waves are evident on altering ice field morphology. MIZ is also the field of interest for commercial stakeholders. Here, we intend to identify knowledge gaps in studying wave-ice interactions.

Knowledge gaps in modelling wave-ice interactions

Wave energy dissipation and change of wave propagation direction due to sea ice depends on wave frequency. Roll-over phenomenon, i.e. wave attenuation rate increases firstly steadily with frequency prior to decreasing monotonically, has been observed in a number of field campaigns. Short waves become isotropic more quickly than long waves and swell. However, roll-over has not been found in all field campaigns. As of late, this phenomenon has not been reproduced in laboratory. The mechanisms, that are conducive to the changing trend of wave attenuation with frequency, are not clear. It has been hypothesized the following processes leading to roll-over: 1) nonlinear interaction between ice floes, such as floe collisions, shearing and rafting among floes, and 2) nonlinear energy transfer among wave constituents having different frequency. At this stage, few efforts have been put on understanding the fundamental physics causing roll-over. Additionally, this roll-over effect may be attributed to scattering effect, which is ignored by previous studies on this phenomenon, both theoretically and experimentally.

As pointed out by Collins et al. (2017), order of wave attenuation rate agrees well among many studies, but primary mechanism in attenuating waves is unclear. Waves in main propagating direction are attenuated by two categories of physics: dissipation and scattering. Proposed dissipation effects include viscosity in water, such as friction in boundary layer and turbulence, and viscosity in ice, such as hysteresis effect, shearing and collisions. Scattering is important if floe size is comparable to dominating wavelength.

Until now, most of the studies on wave attenuation assume Airy waves, hence exponential attenuation of waves. In contrast, some field data suggest linear attenuation for storm waves (Kohout et al., 2014) and nonlinearity (Squire, 2017).

In addition to attenuation, the dispersion relation for wave in ice differs from the one that is valid in open water. Historically, field studies neglect the determination of wave dispersion relation due to technical difficulties to measure wave period and wave length concurrently. In recent decades, stereo-imaging, combination of marine radar with wave buoys, LIDAR scanner and SAR remote sensing techniques provide great potential to determine wave dispersion relation.

In the last half century, many mathematical models have been developed to numerically replicate full-scale wave-ice interactions. Ice is either modelled as discrete mass point, thin elastic plate, a viscous layer, viscoelastic solid layer (see Squire et al., 1995, Squire, 2007, aslo references therein, and Marchenko, 2016) or viscoelastic fluid layer (Wang and Shen, 2010). Viscoelastic fluid layer model (hereafter referred to as VSWS model) is currently the most accepted model, because it converges to discrete mass point, thin elastic plate and viscous layer models at its limits. However, this model is complicated, namely, because the root selection criteria have to be refined based on physical arguments. In addition, the VSWS model does not consider the free edge effect (see Sree et al., 2017), i.e. shear force and bending moment at the free edge are zero. As a recent development, Mosig et al. (2015) extended the thin elastic plate model, according to correspondence principle in viscoelasticity theory, to account for viscosity of ice by introducing complex Voigt shear modulus. This model is henceforth denoted as VSM model.

Fidelity of these models are usually validated using full-scale field data. Nevertheless, the available measurements of ice property need a lot of improvements. Ice thickness varies significantly even in a small spatial scale. Determination of ice thickness distribution in large areas by the current techniques, i.e. local sampling, appears to be unrealistic. Kinematic viscosity and shear modulus are used in both VSWS model and VSM model. However, common testing machines are inapplicable to measure shear modulus of certain ice types, such as frazil and grease ice. Contemporarily, inverse method using field data is applied to obtain the effective viscosity and shear modulus. To calibrate the aforementioned latter two models, these parameters are estimated from a part of field data, before being given as input to models to predict the wave attenuation rate in other test runs in the same field study (Cheng et al., 2017). Inverse method (see Li et al., 2015 for more detailed discussions) inherently implies potential substantial variability, which originates from the possible unidentified parameters. Furthermore, potentially low sensitivity of predicted result to input parameters may result in unreliable calibration (Li et al., 2015). Therefore, new methodology may be needed to determine kinematic viscosity and shear modulus accurately.

In comparison with field campaign, laboratory experiments are more economical and provide controlled situations, in which systematic studies are possible for one or several physical mechanisms isolated from other complicated effects. Laboratory studies have been performed to study wave attenuation and wave propagation in grease ice, pancake ice and mixture of frazil and grease ice or pancake ice. In contrast, laboratory investigation of wave spreading in ice fields awaits to be conducted.

Conclusions

When propagating into icy waters, wave amplitude reduces, wave propagation direction changes and wave dispersion relation alters. How the wave attenuates with traveling distance into pack ice still needs much more efforts to quantify contributions from different mechanisms, i.e. scattering, dissipation, and nonlinear wave energy transfer, etc. The question, in which regime scattering dominates and dissipation is more significant, remains to be answered. New development in measuring techniques offers great opportunities to increase knowledge of dispersion relation of waves propagating in ice covered waters. Determination methodologies of equivalent shear modulus and effective viscosity used in viscoelastic model need further improvement to reduce uncertainties. Laboratory study of wave spreading needs to understand better its implications for wave energy attenuation.

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A new generation of lifeboats, provide an optimized cold climate concept

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The need for a lifeboat that operates in open water, ice and icy waters

Evacuation from ships and fixed installations in maritime operations is a challenging process, especially in severe weather conditions e.g. in cold climate. SOLAS regulations and the Polar code recommends a number of actions related to the evacuation process including a survival for a period of five days in a lifeboat. Today's evacuation systems are not able to fulfill the requirements. This unambiguous safety shortage between regulatory rules and functional abilities creates an uncertainty in risk assessments during an evacuation process. Therefore, it is of importance to bridge the gap and design lifeboats that fulfill the SOLAS regulations and Polar code. The maritime operations in cold climate requires have certain needs for a new approach to design new and innovative solutions in order to establish a safe evacuation process, from launching to seal level and all the way to being saved and located on a ship or on-land. The evacuation equipment's has traditionally been using proven technology, simple solutions and low-cost alternative where performance is not a prioritized area (a solution that hopefully never be used)
The development of lifeboats have since mid-1850 been traditionally developed. The propulsion has been developed from sail and rowing to a movable system with a motor. However, when covering the rescue boat as windshield for the evacuees, then the risk assessment did increase, as the lack of performance requirements for ventilation created new risks. For example, the risk of CO_2 accumulation, not optimal thermal protection or dehydration may be increased significantly. On the other hand, an action when opening the door in order to ventilate the evacuators' area, will most likely then create a negative cooling process that can be shortening affect the temperature on-board the lifeboat.

The SAREX test expeditions, which were carried out north of Svalbard, in April 2016 and May 2017, indicated severe shortcomings in the evacuation equipment design and operating performance. Therefore, this paper will proposed a concept study to design an operating ability that manage to operate in severe weather conditions e.g. ice, ice sludge and water with no ice.
The development of today's solutions and functions in lifeboat performance has not been using the latest technologies, e.g. the existing knowledge from for example the car or aviation industry. The lack of successful evacuation in cold climate, where e.g. ice or icing, fog, polar-lows often is present, is in today's rescue boat solutions a challenging task. In ice-covered water, ice sludge or waters with no ice, there is a need to design lifeboats that are able to manage all these kind of environment challenges in connection with with cold climate, fog, big waves, intense snowfall ice, ice floes or even polar bears. Also ice ridges or floating ice can result in hazardous conditions, that has to be coped with in high north activities in ship traffic or other onshore operations.

A new concept

A new newly adopted certification for ships entering into the Arctic waters and/or Antarctica is from 1 January 2017 in operation, that will fulfil the minimum requirements from IMO Polar code. However, the certificate will not guarantee a safe evacuation process. The Rescue ball concept is designed to provide a more efficient functionality and to handle many of the shortcoming in the design of today's lifeboats. The expected result is then expected to perform a safer evacuation functionality and a thorough risk assessment.
A detailed presentation of the design will show the advantage of managing evacuation in cold climate operations in a safe manner, where the evacuated persons will be able to perform a dry evacuation. This means that the persons will not come in contact with water and as well as avoid a direct connection with the harsh environment outside the rescue unit. As for example, in today's rescue operations in hash weather conditions, the only way of being evacuated from a rescue boat or draft by a helicopter is to enter the water before being lifted up. In wet evacuation, studies show that the energy loss in water at sea is 25 times faster than air (ref SARINOR) and the survival time is then reduced considerably. In dry and semi-dry (life boat / life raft) evacuation will increases the expected survival time and right rescue equipment characteristics for survival support will be crucial.
Therefore, a new design direction will be an important task to introduce dry evacuation procedures, in order to improve the survival conditions up to five days. This survival performance also include an efficient ventilation system and a smart energy consumption.

Conclusions

Today's lifeboats and raft are not working according to what is expected in national and international standards and regulations. There is a need for new types of lifeboats that are able to work cold climate, where condition like in open waters, compact ice, as well as in ice sludge are present. Although new rules to secure a minimum standard has been performed, to certificate ships that will operate in Arctic/Antarctic waters. However, according to this minimum standard in the Polar code, there is no demands to have an evacuation system that operates in cold climate to manage ice, or ice sludge for up to 5 days.

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AIRPORTS AND OTHER LARGE CONSTRUCTIONS

Thule Air Base: High Arctic Airfield Rehabilitation and Reconstruction

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Background

Thule Air Base (AB) was constructed in 1951 and 1952, to include a 3000 m flexible pavement runway with associated taxiways and aprons. Permafrost thaw settlement began to occur in 1952 causing localized depressions in the runway and taxiways. White painting was initiated in 1954 to prevent further degradation of the ice-rich native permafrost sub-grade and continued for over five decades. This practice however greatly reduces braking ability of the aircraft and dramatically increases maintenance and labor costs. A multi-phase investigation was conducted to understand the justification and efficacy of the painting, and to suggest alternatives that could be utilized during the latest repaving cycle. The results of the study show that white painting can be effective only if the color is maintained in a pristine condition, however, through the half century of paint application at Thule AB, a moderate white condition has existed at best. Additionally, and most importantly, ice-rich permafrost does not exist at thermally sensitive depths under the entire airfield, negating the need for thermal treatment across the entire airfield. Alternatives to the extensive white painting were contemplated such as sub-grade insulation, and 'over-excavation' of the ice-rich sub-grade soils.

Approach

The original topography of the proposed airfield area required filling to make grade between cut locations, and as-built information depicts five definitive cut sections with intervening relatively deep fill areas. The design fill thickness for the airfield embankments was determined to be a minimum of 2.0 m (ACFEL 1955) to provide adequate thermal resistance and prevent thawing of the ice-rich sub-grade. However one cut section 450 m in length, was constructed with only 1.0 m of fill thickness along the southern edge of the runway. This was due to changes in the runway cross-section during construction, from a transverse south-to-north down slope, to a crowned cross-section. To mitigate this, a 'box' excavation was constructed in that section along the south edge of the runway lowering the bottom of the cut to 1.5 meters. Additionally a study was conducted to understand the effect of white paint and the potential use as a thaw mitigation tool. It was found that areas of natural black pavement would experience approximately 2.0 m of thaw, while areas with fresh white paint the thaw depth was approximately 1.2 m (Berg and Aitken, 1973). Due to regulations on airfield surface colors and also operation unknowns regarding ground ice proximity and sensitivity, the painting increased in total area over the decades to eventually include the entire airfield (> 372,000 m^2). The frequent paint application caused smoothing of the micro-texture of the asphalt greatly reducing braking ability. This particularly was a problem as rain increased the possibility for hydroplaning in the summer, and hoar frost development on the white painted surfaces created slick conditions in the winter. Daily brooming was required for removal of rain and frost, and this process consequently removed the paint. Overall, the white painting was a substantial safety, cost, and logistical burden.

The geological/geotechnical character of the airfield was investigated with a total of 84 boreholes drilled to understand the source of thaw depressions and obtain geotechnical data. Excess ground ice was discovered either in the form of wedge ice associated with the extensive polygonal ground of the region, or segregation ice associated with decomposed bedrock. Ground penetrating radar (GPR) was utilized to measure depth to the icy horizon and also the total embankment fill depth. While capacitive coupled electrical earth resistivity (CCR) and earth resistivity tomography (ERT) were utilized to map changes in ground ice extent and changes in soil class. It was possible with the GPR imaging to trace the native ground surface over 95% of the length of the runway, which validated the topographic information of the original ground surface and the extent and depth of the cut and filled areas of the runway embankment. It was determined that approximately 18% of the runway (540 m) has a fill depth of 2.0 m or less, therefore requiring thermal mitigation, and considerably less area (<2%) was identified across the taxiways and aprons.

An albedo study was conducted to understand the effectiveness of the white painting (Bjella, 2013). We utilized a solar radiation albedometer and measured areas with differing stages of worn painting, no paint, and bare soil. At these locations the GPR system was used with 400 MHz antenna, to measure the thaw depth for the various albedo measurement locations. Identification of the active layer depth with GPR during test pit excavation and drilling had an error of +/- 6.0 cm. For the brightest of paint, the albedo approaches 0.60 and the thaw depth is approximately 1.2 m, while the natural black surfaces approach 0.12 with thaw depth just deeper than 2.0 m. These measurements demonstrate that the effectiveness of the white paint, if in pristine condition, can reduce thaw depth up to 0.8 meters. If the white paint is slightly faded, removed, or the area includes patches of dark color among bright white, the albedo is greatly reduced and the thaw depth mitigation loses up to 50% of its effectiveness.

An alternative to painting is the installation of extruded polystyrene insulation (EXPS - rigid board insulation) below the pavement asphalt at some optimal depth (Esch 1986). The effect of the insulation was modeled with one-dimensional and two-dimensional thermal solutions, and also tested in full-scale test sections constructed at Thule AB. Three test sections were utilized; one section was constructed with 10.0 cm EXPS, and a second with 5.0 cm EXPS, both with 1.2 m of compacted fill cover. Last, a control section was constructed with no insulation. Temperature measurement sensors were installed in each section with a data logging system and the results are shown in Figure 1. During the month of August 2011, the thermal offset is over 12°C in the vertical distance of 12.0 cm using 10 cm insulation, and 10.5°C using 5.0 cm insulation. This test was coincidentally timed as the summer of 2011 was the 4th warmest on record at Thule AB.

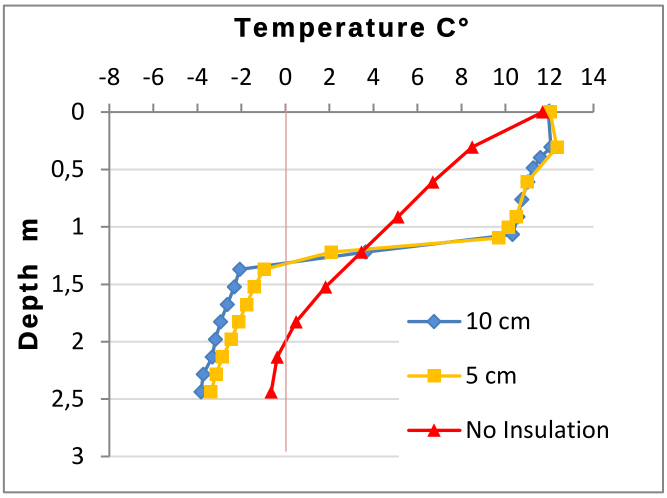

Figure 1. Insulation test measured on 6 August 2011.

Conclusions

This investigation revealed that only 18% of the runway is thaw-sensitive and in need of thermal mitigation, and a very small percentage (< 2%) of the taxiways and aprons were in need of thermal mitigation. In these thaw sensitive zones, over-excavation of the ground ice by approximately 1.0 m to 1.5 m below the active layer was determined to be time and material intensive, requiring significant equipment resources to insure completed excavation and filling/compacting in the short summer construction time frame. Additionally, extensive engineering controls would be required to insure specified ground ice removal was accomplished. Both of those conditions are difficult to satisfy in High Arctic remote locations. Therefore installation of EXPS insulation was chosen as the applicable method for thaw mitigation to replace the white painting. In the thaw sensitive areas, the insulation was placed full-width of the runway/taxiway at 1.2 m depth below the pavement profile, with two sheets of 5.0 cm EXPS, over-lapping at the joints.

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Permafrost Sciences in Support of the Improvement and Adaptation to Climate Change of the Iqaluit International Airport, Nunavut, Canada

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Introduction and Background

Iqaluit is the territorial capital of Nunavut. Its airport is a hub for air transport in the eastern Canadian Arctic, a part of the country without any road connection with the South and served by ship only a few weeks every year. The airport was built in the urgency during World War II by the American army; it was enlarged during the subsequent years of military and civil operations. Since then, it underwent repairs and upgrades repeatedly as any transportation infrastructure. Its paved runway can welcome all the types of aircraft that fly in transit along the Arctic routes, whereas many private, commercial and military flights make it a technical stopover.

An archival compilation of maintenance works and repairs to the paved infrastructure during the last 70 years revealed that, for the most part, damages were caused by structural failures associated with the presence of permafrost and caused by frost, thaw and thermal contraction processes related to the Arctic climate (Mathon-Dufour, 2014). The runway, the taxiways and the aprons are regularly subjected to heave and subsidence due to the annual freezing and thawing of the active layer. Some areas underneath the infrastructure, where the soil is fine-grained, are very frost sensitive and unstable. Historical records also state the recurring repairs of important and numerous frost cracks in the paved surfaces caused by the recurrent thermal contraction of underlying ice wedges. Underneath these frost cracks, the partial melting of these wedge-shaped ice masses in the ground causes linear settlements, with negative impacts on the running surface of the runway.

Since the early nineties, climate has warmed significantly. This region has seen an increase of about 2°C in the past 26 years and the projected climatic scenarios forecast a possible additional increase of 1 to 4 °C in winter and 0.5 to 2 °C in summer by 2030 (AMAP, 2017). As in the case of numerous other important infrastructures in the Canadian Arctic, permafrost at the Iqaluit airport has never been studied and was not characterized before construction. At the time, permafrost was considered to be a solid and permanent foundation for infrastructures. Because of the new concerns related to global warming in permafrost environments and the risks associated with thawing permafrost, the Iqaluit international airport was the object of a detailed study that started in 2010 with funding from Transports Canada and the Government of Nunavut. The main objective of this project is to provide integrated geoscientific data on permafrost to support decision-making and for selecting adaptation measures to mitigate the impacts of climate change. Specific objectives are to:

1. Characterize general and local permafrost properties;
2. Monitor the infrastructure and the adaptation strategies implemented;
3. Proceed to geothermal modelling under projected climate change scenarios;
4. Produce tools of diagnostic and risk assessment for stakeholders.

Geoscientific framework and methodology

Our methodology for permafrost characterization was developed first in Nunavik for sensitivity assessments and design of adaptation strategies for airports and communities (Mathon-Dufour and Allard, 2015). Numerous methods and techniques were applied, including photo interpretation, archival research and analysis, geophysics, permafrost drilling and coring, ground temperature and water level monitoring, numerical modelling, spatial data compilation and interpretation in a GIS application. Mapping of surficial geology and pre-construction and actual terrain conditions, such as drainage network and landforms indicative of the presence of ground ice, were produced by interpreting aerial photographs dating back from the initial phases of construction (1948) to recent high-resolution satellite images (2017). Archival reports and other documents were examined to retrieve all possible relevant information about the airport history, such as expansion projects, permafrost related problems and repairs. A total of 24 deep boreholes (~ 8 m) and 7 shallow boreholes (~ 3 m) were drilled in natural terrain, embankment shoulders and paved surfaces. Nine drill holes were instrumented with thermistor cables and 14 were equipped with piezometers. In order to better characterize the cryostatigraphy, twelve of the holes were cored to extract intact permafrost samples. Frozen permafrost cores were scanned using computerized tomography (CT-Scan) and used for laboratory analyses. CT-Scan image analysis allowed the identification of cryostructure in the samples and the quantification of air, soil and ice contents. Conventional laboratory analyses were performed on selected samples to determine geotechnical properties. Ground Penetrating Radar (GPR) was used to delimit cryostratigraphic units and locate features, particularly cracks and ice wedges in the embankments and the surficial deposits.

Conclusions

The results obtained through this study confirmed that the initial terrain conditions prevailing before the airport construction, such as surficial geology, ground ice and the drainage network, still have an important impact on the current stability and the behavior of the infrastructure. The drilling of permafrost cores, mapping of surficial deposits and geophysics revealed that there is ice-rich near-surface permafrost and massive ice bodies, such as ice wedges, which could continue to generate thaw settlements, loss of bearing capacity and voids in the foundation, should the climate continue to warm.
In addition, the presence of the infrastructure itself, combined with global warming has an effect on surface conditions, such as surface albedo and drainage network modifications. This leads to an adjustment of the permafrost thermal regime to these new conditions. As a result, thermal profiles located under asphalt pavement show warmer thermal profiles and a faster, deeper and longer thaw penetration than sites in the shoulders and the natural terrain, causing the pooling of water in the active layer under paved surfaces. In turn, water accumulated within the active layer causes a positive feedback loop and accelerates the ongoing degradation process. Numerical modelling of ground thermal regime under various scenarios at two thermistor cable sites revealed that short-term changes will affect the ground thermal regime near the surface and long-term changes will affect the ground thermal regime at depth.

This newly acquired geoscientific data on Iqaluit international airport's permafrost has oriented risk analyses and choices of adaptation strategies implemented at the Iqaluit airport during the recent improvements, such as the design of the new taxiways, apron extensions, crack repairs and drainage, in order to make a modern infrastructure that is better adapted to the impacts of climate warming. The collaboration maintained with the stakeholders during this project has proven to be successful in many ways and maintaining this collaboration is essential to assess the performance of the infrastructure and the newly implemented adaptation strategies. In this context, the geoscientific data and instrument network established during this project now provide essential input for decision-making and future risk analyses related to climate change.

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An Integrated Permafrost Science Framework to Support Adaptation of Northern Transportation Infrastructures for a Changing Climate: Case Studies From Nunavik, Northern Quebec

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Introduction

Nunavik is a vast territory located in the northernmost part of Quebec. Inaccessible by road, year-round air links and shipping in summer are the only available means of transportation. Between 1984 and 1992, the Québec Ministry of Transportation built twelve community airports in the region. Three of them are located in the discontinuous permafrost zone and nine are in the continuous permafrost zone. The unpaved runways and access roads were set on thick embankments of crushed rock fill placed on undisturbed ground surface to prevent thawing of the underlying permafrost. However, starting around 2000 under a fast warming climate, many of the runways began to be affected by localized differential settlements due to permafrost thaw. With the anticipated continued rise of air temperatures, corrective measures and an adaptation strategy had become necessary. Preliminary studies initiated by MTQ were undertaken by CEN and the Civil Engineering department of Laval University to evaluate the permafrost conditions at these airport sites in Nunavik. The next step consisted in designing a research program to better characterize permafrost at eight airport sites identified as sensitive and to design custom made adaptation strategies for climate change. Specifically, the objectives of the climate-change adaptation project were:

1- to characterize in details the permafrost conditions at the eight airport sites.
2- to understand the origin and dynamics of the ongoing permafrost degradation processes leading to infrastructure deterioration.
3- to develop the required predictive capacity to evaluate the thaw settlement related to permafrost disturbance under a changing climate.
4- to plan customized adaptation strategies to minimize permafrost degradation to ensure infrastructure stability and users' safety.

Methodology

The permafrost characterization program for each airport site included a geomorphological and geotechnical investigation campaign involving surficial geology mapping and recovery of undisturbed frozen cores using a refrigerated drilling system. In total, 32 boreholes were drilled beside the embankments, allowing the recovery of more than 200 undisturbed frozen permafrost samples. Borehole information was used to reinterpret geophysical surveys made in previous studies (Capacity Coupling Resistivity and Ground Penetrating Radar) in order to produce stratigraphic cross sections of permafrost conditions under the embankments. Lab tests on undisturbed frozen samples, including thaw strain tests, were performed to determine geotechnical properties of all representative stratigraphic units under subgrade materials. Extrapolation of the geotechnical properties measured on borehole samples to surficial geology unit allowed delineation of sensitive permafrost areas. All the geoscience data were integrated into a geographic information system revealing spatial relationships and patterns between observed infrastructure degradation signs, surface conditions (surface drainage, snowdrift accumulation, etc.) and permafrost conditions. Dominant factors responsible for the ongoing permafrost degradation processes leading to the acceleration of the infrastructure deterioration were then identified (diagnosis). Based on collected geoscience data, geothermal models were calibrated based on surface conditions, soil stratigraphy, soil thermal properties and recorded temperature regime obtained from thermistor cable data. Numerical modelling of the thermal regime alongside and beneath embankments and subgrade was then performed to confirm the ongoing permafrost degradation processes and to evaluate how they will evolve under different climate change scenarios. For each site, two MRCC climate change scenarios were chosen as input in the model to give a range of potential values for thickening of the active layer and thermal changes in depth for the 2010-2050 period. Model outputs were used to evaluate the amplitude of thaw settlement to come. To plan optimal adaptation strategies, sensitive permafrost zones were mapped based on the ground conditions and the projected thermal changes proposed by the MRCC climate change scenarios. Depending on the size and location of the sensitive permafrost zones, the characteristics of the infrastructure (embankment thicknesses, widths, slopes, etc.), the role of water (surficial or groundwater flows) and snowdrift accumulation in the permafrost degradation processes, site-specific mitigation techniques were proposed to minimize further permafrost degradation and, in some cases, to even restore initial thermal conditions.

Results

Localized damage on embankment shoulders such as cracks and settlements confirms that the permafrost beneath the shoulders is greatly degraded. In fact, thermal measurements and drilling information reveal that unfrozen layers (taliks) reaching up to six meters deep are now present at the toe of many embankments. Those observations highlight the underestimated importance of snow insolation and latent heat input through summer-warmed water seepage in the permafrost degradation process occurring alongside the runway's embankments built on thaw sensitive ground. Our interpretation suggests that the permafrost degradation process alongside the embankments was initiated soon after the construction of the infrastructure due to the modification of snowdrift accumulation. Those modifications initiate positive feedback mechanisms with cumulative thermal impacts on permafrost that accelerate those resulting from the recent climate warming. For the central part of the runways, thermistor readings show that the active layer is, in most cases, still contained in the embankment or within the prior to-construction consolidated active layer except for localized cuts and thinly filled areas where it penetrates into the permafrost. According to our numerical modelling, as the climate warms up, active layer in the centerline of the runway built on ice-rich permafrost will slightly increase synchronously and proportionally with the anticipated rise of MAAT, resulting in limited thaw settlement. To maintain the centre part of the runway in proper conditions, periodic reloading and profiling of the surface will be necessary. On the other hand, embankment toes will keep degrading rapidly according to the combined effect of snow and water accumulation. This will lead to significant subsidence or embankment failures, thus jeopardizing the long-term stability of the infrastructure and users' safety. Thermal modelling also suggests that permafrost will keep degrading inward and affect the centre part stability of the embankment if no precaution is taken to avoid any potential heat input through summer-warmed water seepage and to reduce the effect of snow and water accumulation alongside the embankment. For this reason, most of the proposed adaptation plans focus on minimizing snow and water accumulation by using specific designs such as the gentle slope embankment (1:7) and convective embankments with heat drains both in conjunction with improved ditch systems. The test site at Tasiujaq Airport actually shows that those mitigation technics are efficient to restore the permafrost under the embankment's shoulder.

Discussion / Conclusion

The integrative permafrost science framework developed during this project is very useful in the guidance of geoscience data collection and analyses to support adaptation of transport infrastructure under a changing climate. The integration of all geoscience data into a geographic information system helps the permafrost degradation diagnose process by allowing spatial relationships between observed infrastructure degradation signs, surface conditions (surface drainage, snow drifts accumulation, etc.) and permafrost conditions. By using this integrative framework, causes of permafrost disturbances and sensitive areas are identified for every site. Site specific optimized adaptation strategies could be selected. The choice of the mitigation techniques was based on identified causes of permafrost disturbance, extent of the problematic area, infrastructure specificities, permafrost conditions and their thermal response to climate warming. These mitigation techniques are now being applied at many sites in Nunavik and a monitoring program is underway to assess their performance.

New Airports in Greenland – a historical and technical perspective

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Motivation

This post will describe the current legislation regarding construction of airports in Greenland. The history of existing airports will be described in order to get a connection with the new planned airports.

Planning and legislation

Laws and Social studies

Construction of new airports in Greenland requires approval from Naalakkersuisut according to the Inatsisartut law No. 12 from 5. December 2008 about airfields. The law states that construction of new airports will only be permitted if the project is able to generate a positive contribution margin to cover the cash capacity costs. For this purpose, a tariff and payment regulation must be drawn up and approved by Naalakkersuisut. The legislation also states that when constructing a new or changing an existing airport, the aerodrome in question must be dimensioned so it improves the overall traffic structure, and if it is publicly financed, the project that provides the largest improvement at the lowest cost should be chosen, taking into account the current and future operators' choice of equipment.

The law requires assessments of the consequences of the construction of new (or changes to existing) airports on the other infrastructure in the country. Furthermore, assessments of the effects of the airport on the environment must be conducted and submitted as part of the application for the project. While the establishment permit is granted by Naalakkersuisut, the authority for project approval during planning and technical approval by delivery is the Danish Traffic, Construction and Housing Agency (TBST). TBST provides also licensing of the operating organisation (which does not need to be the owner or the builder of the airport). However, the Naalakkersuisut can provide 5 years of operating licence.

The technical design

In the initial phase many possible locations must be considered and those locations which best meet the often self-conflicting demands must be selected for further studies. The usefulness and cost must be estimated, and the data used in the business case, the social and the environmental studies.

Airports in Greenland must be built according to specifications in Danish and international legislation and guidelines, such as 1) the Danish BL3-2 "provisions for the establishment of public IMC airfields" version 2 of 10. March 1993 and/or 2) ICAO Annex 14, Volume I, Chapters 3 and 4. This includes considering the Obstacle Assessment (OAS) and Obstacle Limitation (OLS) surfaces as well as airplane approach angles.

To plan the design a map must be made. You need to know the landscape up to 15 km from the centre of the airport in the direction of the runway and about 3-4 km to each side. If GPS based approach procedures are considered, maps in a circumference of 50 km around the airport are needed.

Design basis

Maps can be graded according to the construction face. The preliminary studies need maps which indicate peaks for mountains and shorelines. A height curve equidistance of 50-100 metres can be used. However, near the airport an equidistance of 10 meter is needed. Once the interesting plan sites are located, a map with equidistance of 0.5 m meter as well as geology near the airports and for the road from the sites to the city must be obtained.

When the final site is picked, further studies on weather conditions, turbulence conditions and geotechnical studies of mountain and earth quality can be carried out.

Existing airports

Kangerlussuaq

Kangerlussuaq Airport was established 7 October 1941 by the United States as a military base called Bluie West Eight. In 1950, the area passed to the Danish state, but due to The Cold War, the area was again taken over by the United States 27. April 1951 as Sondrestrom Air Base. In 1992, the Americans left the area and the airport became a civil airport.

The runway was established under a different building code according to the time, but mainly because the runway was established as a military base during a war, Greenlandic and/or Danish wishes and needs were not taken into account in the design.

Runway dimensions are 60 x 2810 m with asphalt pavement and the strip dimensions are 300 x 3015 m, AIP charts displays several breakthroughs in the fly zone and there is a possibility of turbulence on approach from northeast even at mild to moderate winds. It is not without problems to use the airport, but because of a stable arid continental climate, it has in practice proved to be a stable airport, with only a few closing days a year. With the correct planning of flights, you can get close to 100% regularity.

Narsarsuaq
The airport was established in 1941 by the United States as a military base called Bluie West One and a hospital was established in 1943. In 1947, the name was changed to Narsarsuaq Airbase. The base was closed in 1958 when the Thule Air base (Bluie West 6) took over the military strategic importance to the Americans. However, after the passenger ship Hans Hedtoft sank in 1959 the airport was reopened as a civil airport and as a base for the Ice Service of DMI. The service was shut down in 2017, as DMI now uses satellites instead of planes for sea ice recognocense.
The runway dimensions are 45 x 1830 m with concrete pavement and 300 x 1950 security zone, AIP charts shows several breakthroughs in the fly zone and possible turbulence for a variety of wind directions. As Kangerlussuaq, the course is built without regard to Greenlandic wishes and needs. The airport is difficult for pilots to use and the regularity is in the low 80s.

Nuuk and Ilulissat
Nuuk Airport was established in 1978 about 3 km from the centre of Nuuk. The runway is 30x950 m with asphalt pavement and 100x1010 m safety zone with gravel. 430 m approach lights to the north. AIP charts shows breakthroughs in the fly zone and there is a potential for turbulence north of the runway.
Ilulissat Airport was established in 1984 approx. 3 km from the centre. The runway is 30x845 m with asphalt and 100x905 m safety zone in gravel. 300 m approach lights for both ends. AIP charts shows breakthroughs in the fly zone. The course is located north-south due to geography which unfortunately is across the most common wind direction. The airport is due to the geography the only course in Greenland which requires STOL aircraft.
Nuuk and Ilulissat were established to increase the capacity to the cities using fixed-wing aircraft and reduce the cost of helicopter operation.

Regional airports
In 1994 the planning of airports in Sisimiut, Maniitsoq, Aasiaat and Uummannaq was started. They were established in late 1990s. Stage 2 with Qaqortoq, Paamiut and Upernavik should have been established in 2002, but Paamiut was postponed to 2007 and Qaqortoq was replaced by Qaanaaq airport. The lanes are 30x799 m with asphalt paving with safety zone of 70x859 m with gravel coating. However, Qaanaaq is 30x900 m with gravel pavement and 80x1020 m safety zone. All courses were performed at sites where the runway could be expanded to 1199 m courses. The courses were established from a desire to make air transport cheaper by phasing out large helicopters and replace them with fixed-wing aircraft.

Future airports

From 2008 to 2010 Naalakkersuisut collected existing reports and studies of airports in Greenland. In 2011, further investigations were started for large airports in Nuuk, Ilulissat, Qaqortoq, Ittoqqortoormiit and Tasiilaq. In 2015 Inatsisartut instructed Naalakkersuisut to kick-start projects for Nuuk, Ilulissat and Qaqortoq, even though the studies required by the law were not yet in place. Inatsisartut bypassed the law demands of social and environmental impact assessments before designing and tendering.
The enlargement of Nuuk is planned to be a "precision runway" with 200 ft decisions height. The decision height requires much blasting for the OAS. Studies for turbulence have been carried out both numerically and in model experiments.
Ilulissat is planned to a new "precision runway" with 200 ft decisions height north of the existing runway, since the larger jets planes can't go down and up with as steep angles as the STOL planes.
Qaqortoq is planned as a Non-Precision runway with 500 ft decision height, and to be located 6-7 km from the city. There are ongoing investigations into turbulence while still monitoring the weather regime at the location.
In 2004 reconnaissance and preliminary estimates were conducted for short runways in Nanortalik, Narsaq, Qasigiannguit and Qeqertarsuaq and regional airports in Tasiilaq and Ittoqortoormiit.
Further studies are still ongoing for regional airports in Tasiilaq and Ittoqortoormiit by other advisors.

Usefulness of Airports

The above shows that it is a difficult and a long process to build and establish an airport in Greenland. However, the building itself is the easy part. It just requires cooperation between politicians, technicians and financiers in the planning and building phase. These groups are accustomed to work together and the goal is tangible. The hard part is to make an airport contribute to the development of society. Like other infrastructural installations, an airport is not a solution but a means to provide development and value increases. The society and users of the airport must change habits and methods to take advantage of the potential of an airport for economic and social development.

Correlation of marine and lacustrine shallow seismic data and boreholes at Ilulissat and Qaqortoq, Greenland

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Motivation

The Government of Greenland founded Kalaallit Airports A/S in July 2016. Kalaallit Airports A/S aim is to build, own and operate airports in Nuuk, Ilulissat and Qaqortoq. In August 2016, Geo began a series of preliminary geotechnical site investigations for the expansion or new construction of these airports. The investigations were executed by Geo in close cooperation with NIRAS and Inuplan, who are consultants to Kalaallit Airports A/S.

The purpose of the geotechnical site investigations was to obtain information on the physical properties of soil and rock underlying the new constructions. Of particular concern is settlement and ground movement beneath the foundations of these new constructions. In Ilulissat, the embankment will extend into a marine bay, and in Qaqortoq the embankment will extend into a lake.
In the summer and fall of 2017, the main focus of the geotechnical investigations were these marine and lacustrine areas, within the working site in Ilulissat and Qaqortoq. In order to locate the areas with largest amount of sediment, superposing the bedrock, shallow seismic surveys were conducted in both places.

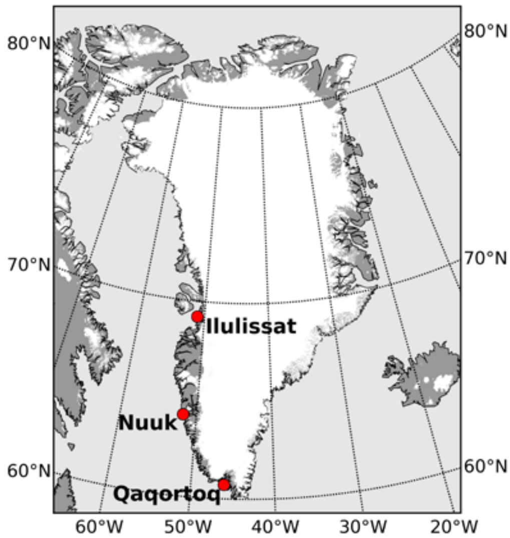

Figure 1. Map of Greenland. The seismic surveys were located close to Qaqortoq and Ilulissat.

This abstract concentrate on the marine and lacustrine shallow seismic survey and subsequent geotechnical boreholes made in 2017 in Ilulissat and Qaqortoq for Kalaallit Airports A/S. The aim is to demonstrate how shallow seismic stratigraphy is a very useful tool in planning and optimizing geotechnical site investigations.

Approach

During the summer of 2017, a number of shallow seismic reflection profiles has been performed in two bays west of the present airport in Ilulissat and in two lakes on the site of the coming airport in Qaqortoq. The shallow seismic survey was followed by a geotechnical borehole campaign.

A setup of high-resolution shallow seismic equipment was chosen in order to map the sediments superposing the bedrock. The seismic equipment consisted of an Innomar SES-2000 Compact SBP (SUB-Bottom profiler) Pinger system combined with a Geo-Source 200 Multi-tip Sparker system including a Geo-Sense 8 element mini-streamer. The positioning of the equipment was carried out by using the satellite based C-Nav 3050 system. Due to the logistic and the scope of work, only the Pinger system (Innomar) was used in the lakes at Qaqortoq.

The seismic vertical resolution, which is the distance by which two different reflections can be discerned, is around 0.3-0.5 m for the Pinger system and 0.5-1.0 m for the Sparker system. The penetration depth for the Pinger system is highly dependably on the geology, but typical in the range 1-10 m, whereas the Sparker system typical are in the range of 30-50 m.

Based on the seismic data, a map of the acoustic basement in both Ilulissat and Qaqortoq has been constructed. With these data, a preliminary interpretation of lithology and depositional environment was made, as a basis for the selection of geotechnical sampling boreholes. Areas with the largest amount of sediments were selected for the borehole campaign. In Qaqortoq the geotechnical sampling boreholes were only implemented in one of the two lakes on the site. Detailed geological descriptions were made of the samples and combined with geotechnical classification laboratory testing.

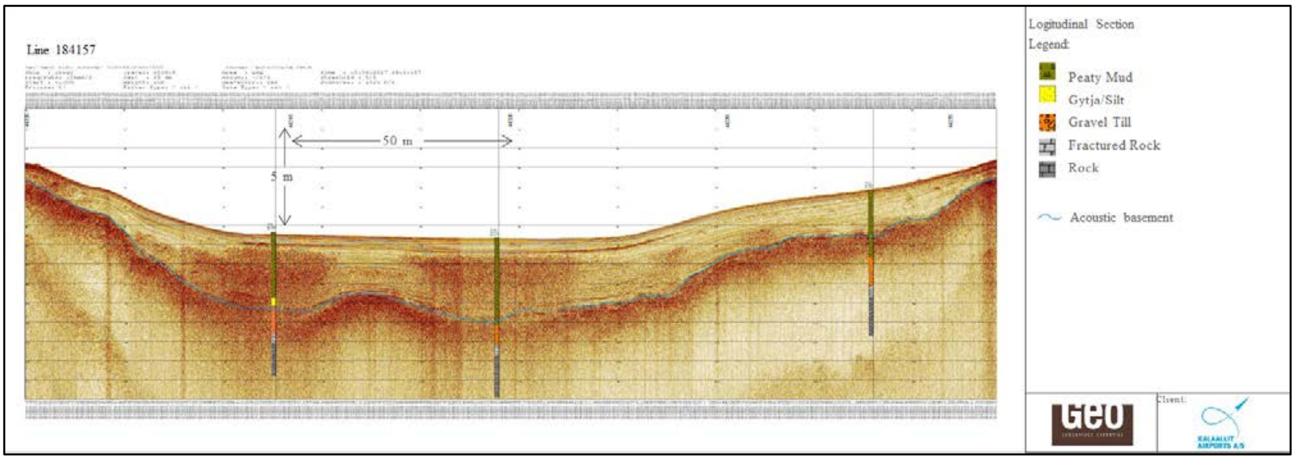

Figure 2. Example of correlation between shallow seismic Pinger data and boreholes in Qaqortoq.

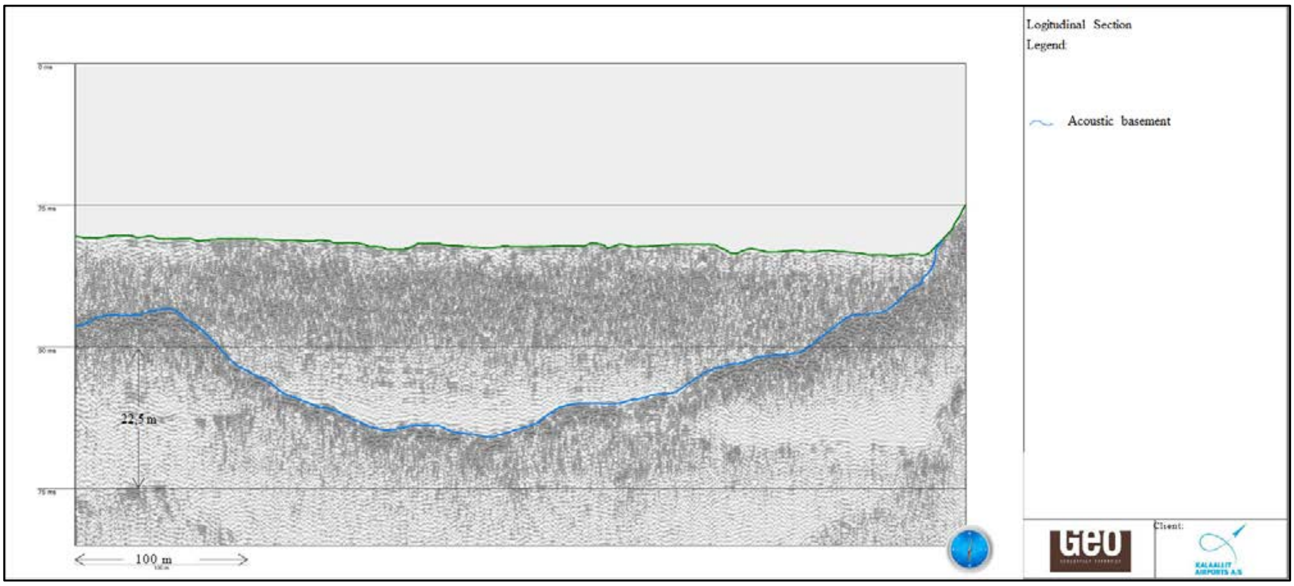

Figure 3. Example of seismic Sparker data in Ilulissat.

The data made it possible to establish the top of the bedrock in the working area in Ilulissat, whereas the acoustic basement in Qaqortoq turned out to consist of gravel and fractured bedrock. In this type of geological settings, the energy from the Pinger system is reflected on the gravel and fractured bedrock. The top of unfractured bedrock in Qaqortoq was therefore primarily encountered through the geotechnical boreholes. The geotechnical behaviour of the sediments superposing the bedrock in both Ilulissat and Qaqortoq was also identified.

Conclusions

From seismic analyses of the data, it was possible to pinpoint the locations with the largest amount of sediment superposing the bedrock. This information made the basis for the selection of the subsequent geotechnical boreholes. As a result, the geotechnical campaign was optimized and the greatest possible amount of data, within the limits of the scope of work, were obtained.

Kangerlussuaq Airport: Establishing a borehole database in support of future operational and maintenance decisions

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Motivation

Greenland is in the process of reorganizing the transportation infrastructure network with the construction of several new airports capable of accommodating trans-Atlantic flights. As part of the changes induced, difficult decisions have to be made regarding the future operation and maintenance of existing airport facilities. Here we discus the geotechnical setting of Kangerlussuaq Airport (67.01°N, 51.69°W) which is currently the main airport hub of Greenland. It was established at a remote and uninhabited site by the U.S. Army Air Forces in October 1941, as an alternative runway to the base at Narsarsuaq and was used as hub and refueling station for transatlantic flights during World War II. Its location was based on the very favourable climatic conditions resulting in high operational regularity.

Background

The airport and its supporting settlement are situated in the rather complex geological setting of a glaciomarine delta in the valley system east of the head of the Kangerlussuaq fjord. Due to its inland location and proximity to the ice sheet, the airport experiences a stable dry subarctic climate with a mean annual air temperature of -3.3°C (2004–2014). Extreme winter temperatures range down to approximately -45°C and summer temperatures up to 25°C. The area has continuous permafrost, the thickness of which has been estimated at 130 m at the airport location (van Tatenhove and Olesen, 1994).

A gravel runway was first constructed in 1941 on the typically coarse grained river plateau; it was strengthened and paved in 1952, and finally expanded (both width and length) to its current size in 1957-58. No excavation and replacement was done during the two first phases of the construction, but for the third phase, excavation and replacement was performed to 3.3 m b.g.s. for the longitudinal extension. The area of the original runway was not reconstructed; the pavement was merely widened to the north. The westernmost part of the new runway extended onto a lower plateau of marine fine-grained sediments affected by deep erosional scars, and a thick embankment was constructed to support the runway (USACE, 1958).

Approach

Based on available blue prints, reports and borehole logs, information about a total of 147 boreholes and test pits in the airport area has been digitized and collected in a database. It comprises information about soil types, water contents, thaw depths and classification of ground ice occurrences, as well as technical information such as drilling date (or year where the date is not available). The information cover investigations conducted from 1952 to 2016 and span different drilling and sampling technologies and both US and Danish site investigation and classification practices – nevertheless, the information has been attempted standardized in a common and intercomparative format. All boreholes and test pits have been georeferenced and their locations are assumed accurate to within 2 m, see figure 1. The collection of the information in a database, allows users to extract statistical information about the occurrence of e.g. soil types, thaw depths or ice content classifications, and link this information to specific areas within the airport. It therefore constitutes a solid factual basis for future operational and maintenance decisions.

Discussion

Based on information from the borehole database, we conclude that the eastern part of the runway is constructed on a river plateau of mainly sand and gravel deposits. Around station 70+00 (2030 m from east end of runway) the depositional environment changes and encountered sediments consist mainly of silt and clay on the lower marine terrace.

Information from 42 holes is available along the runway, 31 of which are located on the river plateau. Most holes on the river plateau (27 of them) contain layers of peat or silt (organic and/or inorganic), the combined observed thickness of which has a median of 0.7 m (maximum 1.4 m) across the area. These materials represent the original surficial eolian deposits and vegetation on which the 1942 runway was constructed. Some holes (7) are not deep enough to observe the lower boundary of these deposits, and thus the maximum thickness may be larger than indicated. All boreholes on the river plateau include coarse-grained (sand and gravel) layers, and the deeper boreholes available show only coarser grained materials

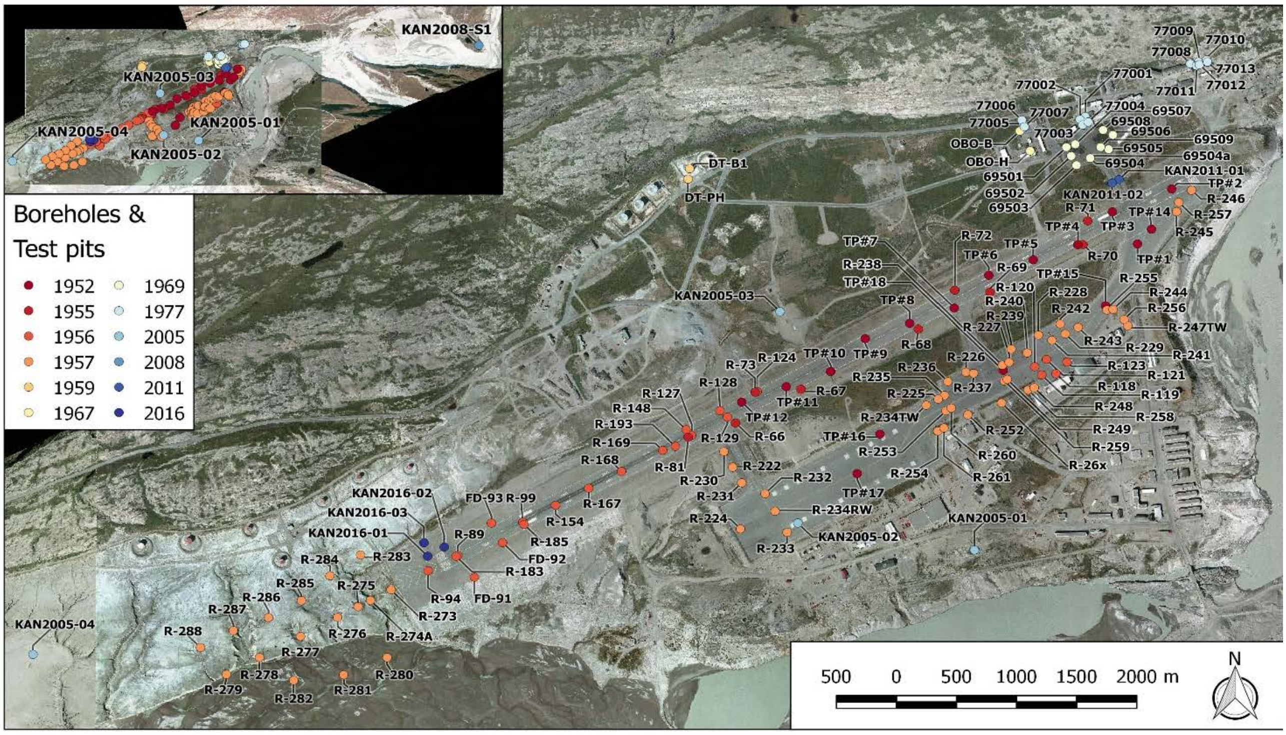

Figure 1. Map of Kangerlussuaq airport with indication of available boreholes and test pits. The color coding represents the year the investigations were conducted.

below the layer of surficial deposits. For the coarse grained deposits the content of fines (grain sizes <0.02mm) where measured is typically low, with an average of 4.7% and standard deviation of 3.5% (N=60). Eight boreholes extend into the permafrost and all available frost classifications indicate poorly or well bonded samples with no segregation ice (NW or NP). The risk of settlements related to permafrost thaw on this part of the runway (stations -6+50 to 70+00) is therefore limited.

Past station 70+00, the embankment rests on marine fine grained deposits of silt and clays of low plasticity (CL and ML). The fines content (grain size <0.02 mm) of available samples average 62% with a standard deviation of 13% (N=63). Much of the materials encountered have been classified as rich on segregationally ice, mainly in the form of regular and irregular lenses and veins (II and IS). In this part, the thermal regime in the ice rich sediments is protected by the thick embankment on which the runway is constructed.

Conclusions

The analysis of boreholes along the runway documents that the eastern part (until st. 70+00 or 2150 m) is located on a river plateau consisting of mainly coarse grained material with low ice content. Surficial organic and silty deposits are present in the subgrade of the oldest parts of the runway, but these deposits are typically of limited thickness. Assuming an active layer thickness of approx. 4 m below paved surfaces (Jørgensen & Ingeman-Nielsen, 2007) all observed occurrences are located in the active layer, and therefore do not constitute a risk related to permafrost thaw, but rather a risk of seasonal frost heave if the pavement is not properly maintained and the construction kept well drained. This is consistent with the fact that no significant thaw deformations have been reported for the western part of the runway.
Severe settlements on the western part of the runway (from st. 78+00) are ongoing, and reported as early as 1971. Based on available borehole and test pit information, these deformations are related to processes in the embankment construction, rather than thaw of the ice-rich natural permafrost subgrade.
Especially the southern taxiways and aprons have been severely affected by thaw settlements, due to the fact that very limited excavation and replacement was conducted during construction.

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Mechanistic Analysis of Frost Action under Pavements

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Introduction

In cold regions frost may penetrate to large depths below the surface of pavements, resulting in the formation and growth of subsurface ice lenses. Such frost action is accompanied by volume expansion that forcefully and unevenly displaces lower pavement boundaries [*1*]. Ultimately, the subterranean deformations result in added distortion at the ride surface - both longitudinally and transversely [*2*]. From a design and construction viewpoint, the adverse effects of frost action can be limited by considering remedial measures such as [*3*]: (i) increasing the thickness of non-frost-susceptible layers, (ii) introducing an insulation layer, (iii) lowering the water table level, and (iv) chemically treating the underlying soil. In essence, these measures aim at deepening the problem source.

In the current work a mechanistic model originally developed for the evaluation of pavements on expansive clays is offered for analysing deformations due to frost action [*4*,*5*]. The model introduces a rational association between imposed subsurface deformations and consequent surface deformations. Conversely, when surface deformations are known, the model can be employed in an inverse analysis to infer on the magnitudes and spatial pattern of frost action under pavements. This framework can be useful for studying the effectiveness of different design alternatives and as an additional input to pavement management in cold regions. Herein, the model basics are reiterated, followed by a demonstrative application.

Modelling and Analysis

The proposed model for analysing frost action considers (see Figure 1) a weightless, isotropic, homogeneous, and linear elastic layer (infinite laterally) with thickness H and material properties E (Young's modulus) and ν (Poisson's ratio). This layer represents the sum of all non-active materials within a pavement system, e.g., asphalt concrete, granular base, aggregate subbase, capping, and treated subgrade soil. Initially, the layer is assumed stress-free and undeformed with both top and bottom boundaries completely flat - as indicated by the dash-dot lines in the Figure. An axisymmetric blister-like displacement field is forced at the bottom of the layer, deforming the lower boundary in the vertical direction without inducing shear stresses at the interface. This deformation, indicated in the Figure by a solid line, represents the effect of frost action.

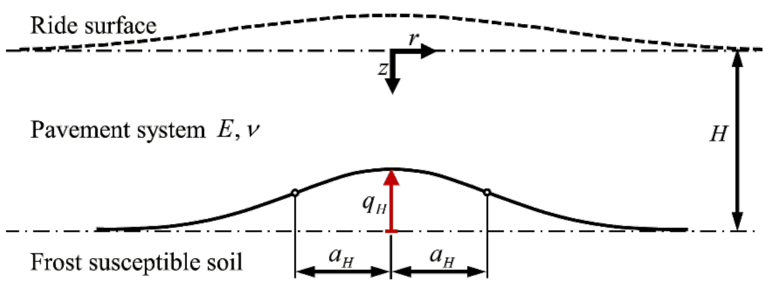

Figure 1: Illustration of basic model definitions with cylindrical coordinate system placed at the top of the undeformed layer.

The model permits calculation of all mechanical response types (i.e., stresses, strains, and displacements) inside the layer as well as at the top - corresponding to the ride surface level. The imposed displacement field at bottom is denoted by u_z^H, mathematically expressed as an axisymmetric Gaussian, i.e. $u_z^H(r) = q_H e^{-(r/a_H)^2/2}$, where r is the radial coordinate, q_H is the peak displacement occurring at $r = 0$, and a_H represents the location of sign-change in the curvature of $u_z^H(r)$, i.e., the so-called Gaussian width. Both q_H and a_H have units of length; a_H must be positive, while q_H can be either positive or negative to indicate downward or upward deformation (respectively). The particular form of $u_z^H(r)$ was chosen because it can serve as a radial basis function for representing any other deformation shapes - not necessarily axisymmetric. This modeling flexibility is needed when simulating realistic situations. The vertical displacement at the top of the layer, denoted as u_z^0, is shown in Figure 1 by the dashed line. The mathematical formulation is given in [**5**]; it involves numerically evaluating a semi-infinite integral.

As a demonstration exercise, the model was applied to the analysis of settlements observed on the runway at the Kangerlussuaq Airport. Kangerlussuaq is the main airport hub in Greenland, and is situated in the continuous permafrost zone. The west end of the runway was constructed in 1957/58 on a thick embankment resting on ice-rich marine sediments. The thickness of the active layer is about 2 m, and the thickness of the non-active pavement structure (i.e. H) is approximately 1.5 m. This part of the runway has experienced severe differential settlements over the past decades. Surface elevation measurements were performed in 1973 (about 15 years after construction). After subtracting the original (as-built) elevations, these measurements are shown in Figure 2 for a certain longitudinal profile (dashed line). As can be seen, over a 400 m long strip, from station 2250 to 2650, the pavement settled unevenly by up to 0.4 m.

Model application to the problem commenced with spatially matching the measured elevation differences $MSE(x,y)$ with a function that is composed of a sum of $N = 6$ radial Gaussians, each having a set of new parameters $q_{0,i}$ and $a_{0,i}$ in place of $q_{H,i}$ and $a_{H,i}$. This is carried out with a nonlinear optimization algorithm to determine the numerical values of the unknown Gaussian parameters. Next, the model was used to find the corresponding parameters for the subsurface Gaussians, see [**4**]. The resulting subsurface deformations are included in Figure 2 (solid line). It can be seen that the top of the active layer practically mirrors the surface shape and that the subsurface deformations are larger than the surface deformations.

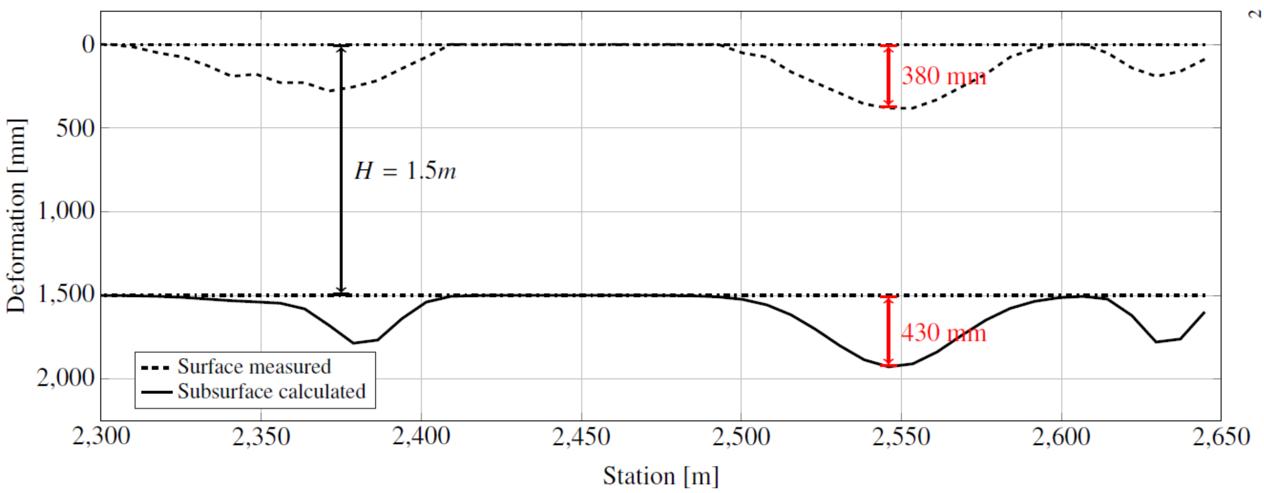

Figure 2: Measured and calculated surface and subsurface deformations.

Summary and Conclusions

In this study a mechanistic model is proposed and applied for simulating the coupled effect of a pavement with underground movements. A Gaussian function was used to represent the axisymmetric vertical deformation field of the runway surface in Kangerlussuaq Airport. The results obtained show that surface deformations can be approximated with a function that is composed of a sum of radial Gaussians. Calculated subsurface deformations were seen to be similar in shape to the observed surface deformations, and of larger in magnitude.

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Sisimiut Airport – Project Investigations, Construction and Stability and Settlements of Runway Founded on Soft Marine Clay

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Motivation

Sisimiut Airport is located 4 km northwest of the town and designed with a runway (799 by 30 m) for Short Take Off and Landing aircrafts Dash-7 and to-day used by Dash-8. The Sisimiut airport and runway embankment was constructed in the coastal area characterized by small rock outcrops intersected with erosional valleys in bedrock filled with soft marine clays over sand and till. It may be considered a type locality for infrastructures founded on soft marine clay. The project investigations were carried out between 1991 and 1995 and consisted of open exploration excavations above sea level and geophysical surveys and boreholes and soundings below sea level to find the rock surface and the geotechnical properties of the overlying marine clays, meltwater sand and till. Especially, the local basins of 4 to 15 m of marine clay with low shear strength ($c_v \approx$ 30 to 50 kPa) and high water contents ($w_{nat} \approx$ 25 to 48% $\geq$ liquid limit $w_{L)}$ called for advanced geotechnical laboratory tests. They consist of oedometer tests and triaxial compression tests in order to establish a safe design profile for the construction of the runway embankment. The valley at the eastern end of the runway with 15 m of marine clay was avoided due to stability cautions and evaluated large long-term settlements. The runway embankment was moved closer to the coast and with the runway west of the deep marine basin as seen in Figure 1. The airport and runway were constructed in the period 1996 to 1999 using compacted local rock fill from blasting rock obstacles and from the quarry at the present Terminal area. Regular traffic started in 2000. Maintenance of the safety zone and the asphaltic concrete paved runway has been very limited due to high quality construction and control methods applied.

Approach

The present case has been used as background for ARTEK courses in geotechnical engineering, road construction and surveying courses in the period from 1999 until today. Site inspections, construction drawings with surveying results from 1998 and 1999 and available geotechnical reports are integrated in our education and research. We have supplied field and laboratory investigations for a possible extension of the runway towards east. Focus has been on refining the consolidation properties in oedometer testing as the soil conditions may call for staged preload of the soft clay deposits in order to refine the stability calculations. Especially, a better determination of the consolidation coefficient c_k as function of stress level

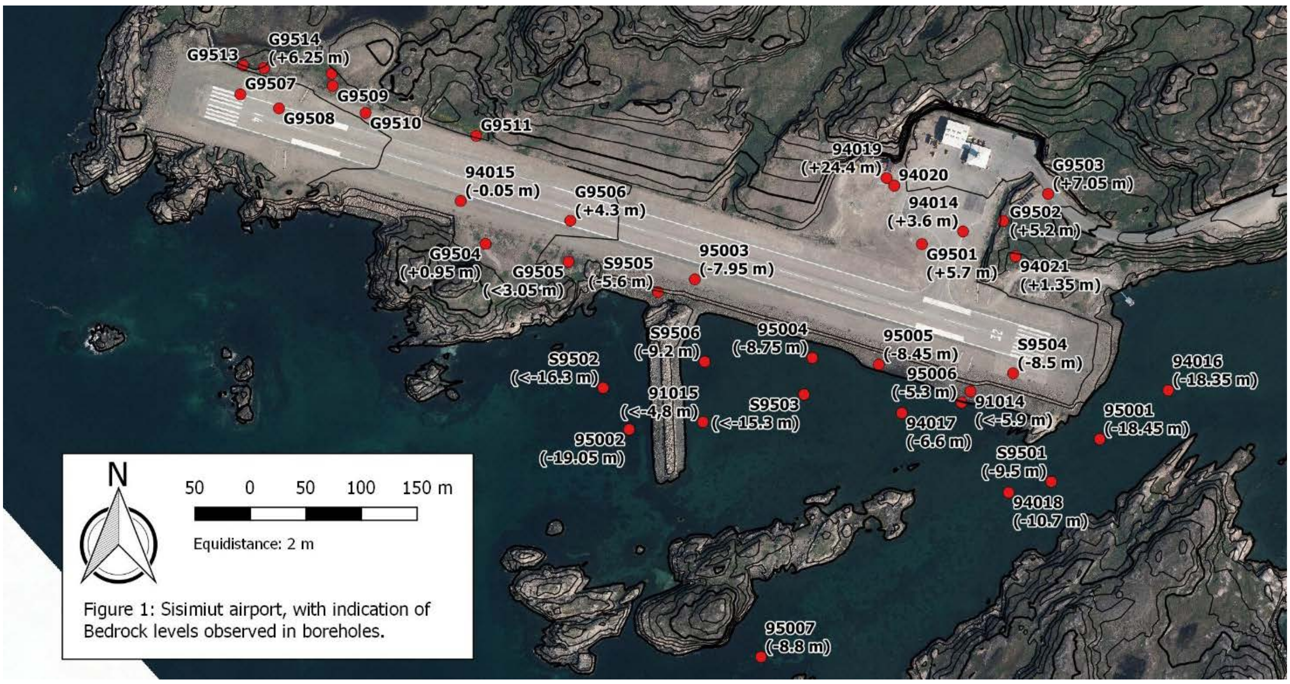

Figure 1: Sisimiut airport, with indication of Bedrock levels observed in boreholes.

has been studied. Actually, this parameter may vary from 2 to $20 \cdot 10^{-8}$ m^2/sec which could lead to a time interval of 1 to >10 years for final consolidation and need for long duration preload duration. In order to verify the consolidation properties we initiated from 1999 systematic surveying of well defined levelling points along the Runway and the Safety Zone and on the Breakwater. In total 8 sets of levelling have been done using available levelling tools and RTK GNSS and eventually a total station investigation in 2016. Some representative results of these measurements are shown in Fig. 2 along the white painted southern boundary of the runway from St. 1255 to St. 1700. In this area the runway and safety zone may rest on up to 5 m of soft marine clay. The differential settlements are 10 to 20 cm of which 5 to 15 cm takes place in the period of 1998 to 2005. This confirms calculations of primary settlements based on the oedometer tests being ~15 cm for rock fill load of 150 kPa on 3 to 5 m soft clay. Additional settlements achieved after the primary consolidation from 2005 to 2016 are caused by relative high values of creep found at preconsolidation stress of 120 to 200 kPa. The largest measured settlement (~50 cm) was found on the breakwater around borehole 95002 where the thickness of marine clay rises to 15m. However, the positions of the large rock boulders may have been changed due to wave and ice actions. The settlements in the western part of runway and safety zone boundaries with very limited amount of rock fill are less than 5 cm.

Conclusions

The project investigations and construction for the Sisimiut Airport may be a type locality for infrastructures founded on soft marine clay. As such it has been a perfect case study for ARTEK education of Arctic Engineers with engineering geological variability, use of geophysical methods and all geotechnical field and laboratory studies. In combination with the systematic surveying it has been very motivating for the students who learned a lot on the practical use and consequence of engineering studies for infrastructures.

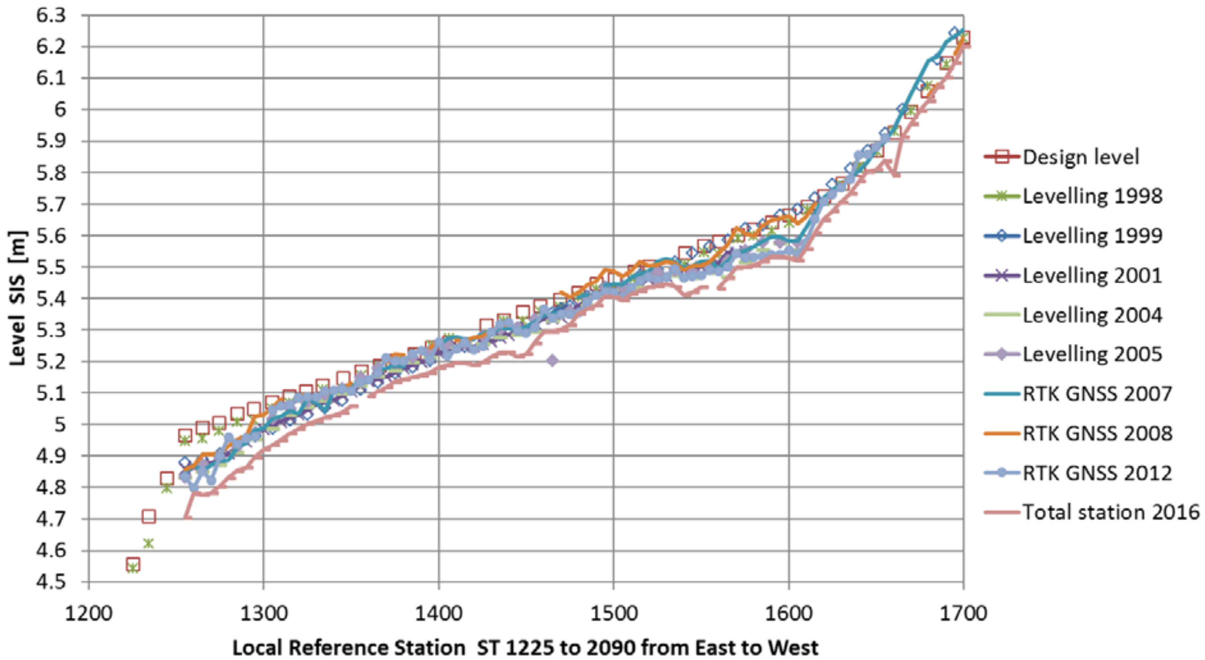

Figure 2: Levelling of southern boundary of runway. Station 1255 m is eastern end of runway.

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Time-lapse electrical resistivity tomography for improved characterization of thaw-sensitive permafrost

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Motivation

Fine-grained permafrost sediments, sometimes with varying level of salinity in the pore water, complicate infrastructure design and maintenance in the coastal regions of Greenland. In spite of ground temperatures well below 0 °C, these sediments may exhibit mechanical properties like thawed soils. Locating and characterizing such sediments in remote areas of planned infrastructure development is a logistically and financially extremely demanding task. High cost of drilling and site investigation campaigns often prevent gaining deeper knowledge about ground conditions.
In this work (Tomaskovicova, 2017), we developed and tested an innovative approach to mapping and describing permafrost sediments. We used time-lapse electrical resistivity soundings collected from the ground surface in connection with ground surface temperatures and numerical modelling to provide an indication about the ground thermal state, depth of annual thaw and freezing point depression. Among the main advantages are reduced logistical and financial burden, better understanding of in-situ processes and soil characteristics and reduced environmental impact of the non-invasive surface method.

Approach

The coupled modelling framework allows inferring ground thermal conditions from changes in electrical response. The electrical resistivity tomography (ERT) is a method that maps electrical properties of a section of the subsurface located below the investigated profile. The method is very sensitive to phase change between water (low resistivity, typical for thawed soil) and ice (high resistivity, typical for the frozen portion of the ground) at sub-zero temperatures.
The approach to recovering ground thermal properties from geoelectrical data is illustrated on Figure 1 and detailed in the following:
The coupled model consists of two, essentially standalone, modules: a heat transfer model and an electrical resistivity model. The 1D heat conduction model calculates the temperature distribution in the subsurface given a set of initial and boundary conditions, forcing ground surface temperatures and thermal parameters. The calculated temperature distribution is translated into a 1D multi-layer geoelectrical model. This is done by dividing the model into many equally spaced layers. For each layer of the resistivity model, the layer-representative temperature is found by interpolating between the nearest grid points of the heat model. For each layer-representative temperature, fractions of water, ice and rock are found using a relation describing unfrozen water content in soils at subfreezing temperatures (Lovell, 1957). The effective bulk soil resistivity for the given model layer is calculated from specific resistivities of the respective ground constituents using a resistivity mixing rule. From the geoelectrical model, the forward apparent resistivity response is calculated by the CR1Dmod program (Ingeman-Nielsen & Baumgartner, 2006) using the same electrode configurations as on the field site. The calculated apparent resistivities are then compared to the field geoelectrical measurements. The difference is minimized by adjusting both the thermal parameters of the heat model and specific resistivities of the resistivity model from which the forward resistivities are calculated. The final heat model calibration is validated by comparing the simulated ground temperature distribution to a borehole temperature timeseries from the location of the time-lapse ERT acquisitions.

A monitoring station for automated measurement of ground resistivity was built near the airport in Ilulissat, West Greenland. The station has been acquiring daily ground resistivity soundings and surface temperatures for development of the model, and ground temperature in three boreholes for model validation.
Our modelling work showed that the resistivity-calibrated heat model reproduces field-measured ground temperatures with an accuracy (±0.55 °C) comparable to a traditional calibration on based directly on measured borehole temperatures. The timeseries of resistivity data are indicative of soil freezing/thawing characteristics, such as the freezing point depression and different rate of freezing/thawing.

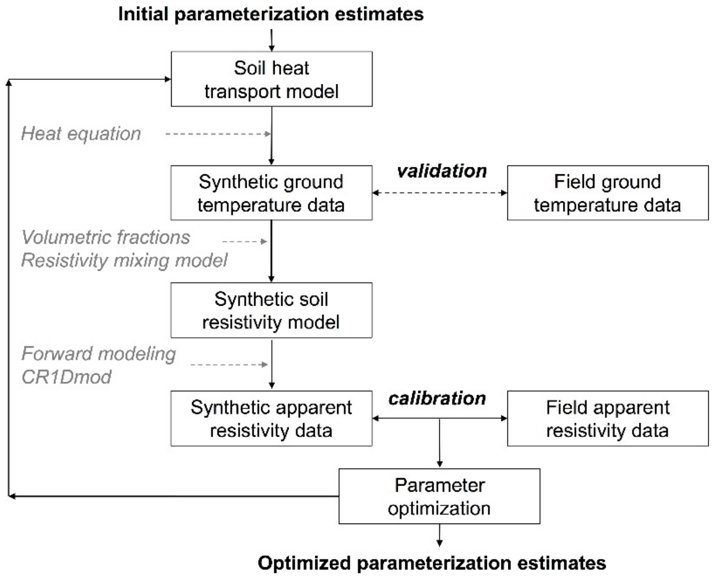

Figure 1: Scheme of the coupled inversion approach.

Conclusions

The calibrated coupled thermo-geophysical model can be exploited for predictions regarding the ground thermal regime following various surface temperature scenarios. For example, a climate change scenario can be applied to estimate a change in annual thaw depth. The model could therefore be used as an indicative tool when designing infrastructure and foundations in permafrost-affected areas.
The main advantages of the method are that it allows to describe the effective freezing/thawing point of the ground (which may be <0 °C), it allows to obtain 2-3D information about soil properties and it is logistically and financially comparatively less demanding than traditional investigation methods (drilling and borehole temperature measurements). The trade-off is securing the permanent power supply for the duration of the measurements.

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Geotechnical Investigations for a swimming center in the rock mass at Sisimiut, West Greenland

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Motivation

For the last 10 years, a swimming center in the rock mass has been in the pipeline in Sisimiut, Qeqqata Kommunia. Over the years, several site studies have been done to find the right location. Last year A.P. Møller Foundation made a donation and the realization of the dream could begin. On behalf of Qeqqata Kommunia, VERKIS Consulting Engineers perform the project design and conduct the tender for the turnkey contract. In the summer 2017 GEO carried out the geotechnical investigation as a basis for the final design. A main concern for the project is permafrost. Sisimiut is located in the discontinuous permafrost zone and it is important to get an overview of the presence of permafrost at the site. Furthermore, determination of stress state in the rock mass is important for the design and orientation of the construction. The focus of this paper is the geotechnical investigation including fieldwork and laboratory testing.

Approach

The fieldwork was performed in august 2017 on a location just south of "Spejdersøen". Five core-drillings to a depth of 50m were performed. The drillholes were slightly inclined 15-30 degrees according to vertical.

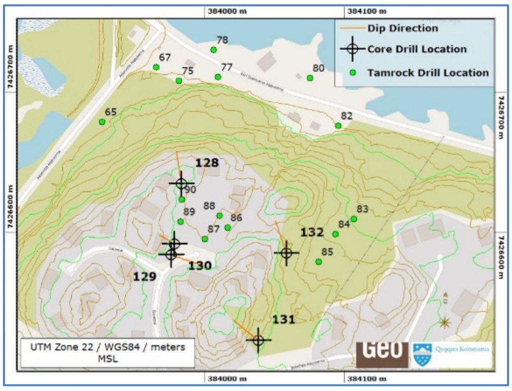

Figure 1: Site plan of geotechnical investigation

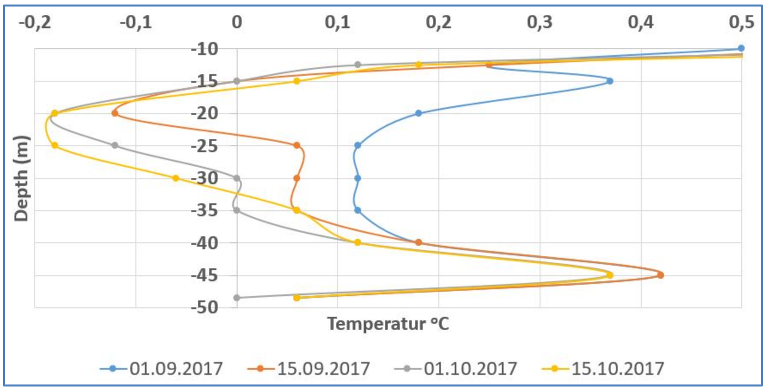

Figure 2: Temperature measurements in relation to depth over time, with 15 days intervals from 1/9-15/10, in borehole B128. Indication of permafrost from -10 to -35 MBGL

To evaluate the rock stress levels and orientation several in-situ rock test by hydraulic fracturing were performed in borehole B128 and B130. The testing was done by SINTEF, Norway. A part of the borehole in non-fracture rock was isolated using an inflatable packer and subsequent pressurization with water in the test section until the rock falls in tension. The in situ stress was estimated by interpretation of the opening pressure, reopening pressure P_{re} and shut-in pressure P_{isi}. An impression packer measured strike and dip of the hydraulically induced fracture plane. We assuming that the induced hydro fracture is oriented parallel with the maximum horizontal stress σ_H in a plane perpendicular to the borehole and the minimum horizontal stress σ_h is perpendicular to the fracture plane.

$$\sigma_1 = \sigma_H = 3P_{isi} - P_{re} - P_0 \quad , \qquad \sigma_3 = \sigma_h = P_{isi}$$

In B128, a large variation in strike and dip of the induced fracture and the inhomogeneity was probably due to the short distance to the mountainside. In B130, further away from the mountainside, the results were more homogeneous and give a better understanding of the strength in the mountain. The orientation of maximum horizontal stress was measured to SSE-NNW. The best orientation of the hall is perpendicular to the maximum horizontal stress and the optimum longitudinal direction of the hallway will be ENE-WSW. Following result were determined in borehole B130: $\sigma_1 \approx \sigma_H \approx 2{,}0$ MPa, $\sigma_3 \approx \sigma_h \approx 1{,}75$ MPa.

Lugeon tests were done to get an overview of the hydraulic conductivity resulting from fractures. Water was injected into a fracture zone sealed between to inflated packers using a slotted pipe, which itself is bounded by the packers. Using the average values of water pressure and the measured flow rate, the average hydraulic conductivity of the rock mass was determined. Lugeon values [unitless] for each test were calculated as follows and then an average representative value was selected for the tested rock mass. Influensradius wasn't known but set to the length of the test interval L (2m). The radius of the drill hole was 24 mm.

$$Lugeon = \frac{Q}{L} \cdot \frac{P_0}{P}$$

(Q - flow rate [l/min], L - length of the borehole test interval [m], P_0 - reference pressure of 1 MPa [MPa], P - test pressure [MPa])

$$K = \frac{Q}{2\pi LH} ln\left(\frac{R}{r}\right)\ L \geq 10r$$

(K - hydraulic conductivity [m/s], L - length of test area [m], r - radius of drillhole [m], R- influensradius [m], Q- well discharge rate (m^3/d), H- pressure [m column of water]). The hydraulic conductivity of the rock mass was influenced by the rock discontinuities. Therefore, the Lugeon value represent not only the conductivity but also the rock jointing condition. The calculated Lugeon values for borehole B128 range from 12,4 to 45,2. According to standard classification (Lugeon test interpretation. revisited, Camilo Quiñones-Rozo) this corresponds to a moderate to medium hydraulic conductivity in the range 6x10-7 to 6x10-6 m/s, and some partly open discontinuities. But because of leaking packers, the true conductivity values are probably lower.
Geological descriptions were made on location and homogenous granitic gneiss to dioritic gneiss with a few amphibolite layers were observed. The degree of jointing was reflected in the measured RQD values and the result shows good quality of hard rock. In the upper meters we observed few weathered fractures as expected.

RQD	B128	B129	B130	B131	B132	All
Mean	80	86	79	91	81	83
σ	10	12	18	12	17	15

Table 1: Average RQD values for each drill hole. Rock quality designation (RQD) = (SUM(length of core pieces >100mm)/Total core run length)x100

In consultation with VERKIS, core samples were selected for testing and sent to Geo's laboratory in Denmark. Point load test, uniaxial compression strength (UCS), and brazilian test (tensile strength) were performed in the laboratory. Unfortunately, the UCS test setup had a maximum load of 100 MPa and the test samples never went to failure mode. In the test there is no evident trend observed between bulk density and stress.

Test	ρ_{bulk}		T_o		I_{s50}		σ_{UCS}
	[g/cm³]	σ	[MPa]	σ	[MPa]	σ	[MPa]
pointload	2,81	0,11	-	-	7,15	0,11	172
Brazilian	2,75	0,07	9,43	1,40	-	-	-
UCS	2,76	0,06	-	-	-	-	>101

Table 2: Average test result for pointload, Brazilian and UCS

Finally, a temperature logger with 20 sensors were installed in borehole B128 for further permafrost testing over a period. Measurements over time with 15 days intervals from 1/9-15/10, shows a stabilization period and temperature touching zero which indicate permafrost from -10 to -35 MBGL. The permafrost will disappear over time because of heating from the hall installation. It is questionable how thawing will change the hydraulic properties of the rock mass. Pressurized water will not freeze because of temperatures very close to zero and minor changes in the hydraulic properties are maybe insignificant for the construction.

Conclusions

The geology and lab results, including RQD, were similar to previous surveys, but as something new permafrost was observed, and rock stress levels and orientation in the rock were determined, which will be important information for the final design and location. In Greenland, the project is ground-breaking for possible future utilization of underground construction for sports facilities, freezing houses, parking basements, power plants and Hydro power stations. Underground solutions will be more competitive in the future and keywords are environmental aspects, topographical condition, safety and lifetime cost.

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STUDENT ABSTRACTS

Artificial Ground Freezing technique for tunnel stabilizing

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Motivation

Harsh environmental conditions prevailing in northern regions, demand special approach for any construction activity. Combination of high effectivity and low environmental risks are considered crucial in geotechnological projects and particularly in underground construction.
One of the most significant issues in arctic geotechnology is to maintain construction stability. In arctic regions with relatively high permafrost layer this task can be solved by protecting permafrost from thawing during construction and operation. [1]
One of the main advantages of construction in permafrost is absence of water flow in soils. Otherwise, if underground constructions are designed in water saturated soils with average temperature above 0 oC it can be required to freeze a layer of soil around the construction to prevent water leakage inside it. This technique is called Artificial Ground Freezing. The technology was patented more than 100 years ago. Since than it has been modified, but the basic principles remain the same. [2]
Based on this technique, soil with average temperature above 0 oC can be frozen and kept at negative temperature during the construction period and if required also during operation of the geotechnical object. The method is used worldwide – from arctic to subtropics for various geotechnical projects [3].
The current paper describes the feasibility of ground freezing as potential stabilizing measure for tunnelling through a soil filled depression at Bergåsen road tunnel.
The tunnel is planned by Statens vegvesen – Norwegian public roads authority – as a part of European highway E6 (from Trelleborg(Sweden) to Kirkenes(Norway).
The tunnel is located in Grane kommune (Nordland fylke in Northern Norwayregion) and is scheduled for 2018 – 2023. [4]
Based on geotechnical sounding it was found that the 1,3 km long tunnel will cross a depression over a section of approximately 20m, which is filled mostly by water-saturated soils (silt, sand and gravel). To "handle" this section, special methods of soil stabilisation are required.
The aim of the current research is to evaluate the feasibility of artificial ground freezing applied to the current case.

Approach

The analysis implemented in this paper, is based on geological and geotechnical reports with description of mechanical and thermal properties of soil. One of the most important factors is ground water flow, which determines the significance of ground water. This parameter strongly affects the required thickness of artificial frozen ground layer sufficient to protect the tunnel during excavation and permanent lining installation.
The analysis of tunnel stability and support requirement is provided by numerical modelling in FEM software "Rocscience".

Results (expected)

The following issues are expected to be solved during the planned research:

- Design parameters of the Artificial Ground Freezing technique, such as time of freezing, energy consumption and costs for freezing
- Indication of stability and support requirement.

Numerical analysis should prove the assumed advantages of artificial ground freezing in comparison with other methods applicable for the tunnel stabilizing, which are theoretically considered as less effective.

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Thermo-Hydro-Mechanical simulations of Artificial Ground Freezing

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Motivation

Hundreds of thousands of people in Alaska, Canada, Russia and Greenland live on permafrost, which covers nearly 24% of the northern hemisphere (National Snow and Ice Data Center, 2018). Living conditions can be challenged by the fragile nature of the frozen ground, especially if framed in the context of global warming. Indeed, permafrost effects like frost heave and thaw settlement may heavily affect existing buildings and transportation infrastructure such as roads, railways, embankments and runways. These being vital for isolated Arctic communities, should be preserved and maintained to avoid any unfavourable happening. Artificial Ground Freezing (AGF) can be employed to keep soil frozen and hence ensure structure stability by means of one-way heat pipe systems, also called thermosyphons. Such devices have been widely used in China where permafrost degradation of the Tibet plateau posed severe threats to the normal functioning of the Qinghai-Tibet railway and in Greenland, where buildings in the settlement of Kangerlussuaq were threatened by the shifting thermal regime of the underneath soil. Furthermore, AGF is also used nowadays as a valuable and efficient construction method for underground engineering projects in densely built up areas, due to the enhanced soil strength and decreased permeability. This technique allows to form earth support systems covering a variety of problems such as structural underpinning for foundation improvement, tunnel constructions and temporary control of groundwater flow in construction processes. A good example is the construction of Naples underground in Italy, where artificial ground freezing has been successfully applied. It seems clear that the interest in frozen ground engineering, whether soil freezing is induced by natural conditions or by human activities, has rapidly developed over the last decades. To predict the coupled thermo-mechanical behaviour of frozen soil and to provide a reliable design tool for geotechnical engineers, the development of a numerical modelling approach is necessary.

Methodology

This MSc thesis aims to back-calculate available measurements of the tunnelling project in the new underground of Naples, using a new constitutive model called Elastic-Plastic Frozen/Unfrozen Soil model, recently developed at NTNU by Ghoreishian Amiri et al. (2016a). Results will be used to validate the numerical model, as little data for artificial ground freezing in cold climate exists as of today but might be used in future. The model is based on the Modified Cam Clay model and it is formulated on the concept of two-stress state, namely solid phase stress and cryogenic suction, allowing to build a complete Thermo-Hydro-Mechanical (THM) framework where temperature, mechanical strength and hydraulic pressure are considered at the same time (Ghoreishian Amiri et al., 2016b). In this MSc thesis, the Finite Element program PLAXIS 2D is used as numerical tool to perform THM modelling of frozen soil for the railway tunnel construction at Municipio and/or Garibaldi stations in Naples. Literature data, obtained by Pelaez et al. (2014) on Yellow Tuff retrieved from the subsoil of Naples will be used to calibrate the constitutive model.

Expected results

The primary aim is to evaluate the accuracy of the proposed model in terms of predicting the temperature and displacement profiles of the ground subjected to artificial ground freezing. It should be noticed, that the model has been previously validated against available element tests data and large-scale test data by Rostami H. (2017) and that the necessary improvement has already been applied. The next step will consist of evaluating the accuracy and robustness of the model in a practical engineering project. Commonly, some improvements will be required to increase the accuracy and to make it even more stable and robust.

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Influence of ice on stability of rock slopes in cold regions

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Motivation

In cold regions, freezing is an important factor for weathering processes in rock slopes. The presence of ice in discontinuities can contribute to maintain the stability of rock slopes. But degrading permafrost and thawing cycles can be considered an important factor for rock slope failures in arctic environments [1]. The project aims to the influence of ice and thawing to the stability of a rock cut rock slope or another type of engineering rock slope. The cycle of ice and thawing will periodically change the stress state in the rock mass and gradually changes the rock physical and mechanical properties, such as weathering and weakening of the rock mass in the long run.
Davies [2] showed through direct shear box test that the stiffness and strength of an ice filled joint are a function of normal stress and its temperature. Results revealed that a jointed rock slope that is stable without ice in the joints and is also stable when ice is present at low temperatures will become unstable as the ice thaws. A direct impact of icing to the rock mass is the wedging effect in rock discontinuities which may influence the stability of an engineering slope in joint rock masses. Permafrost dynamics influence the rock slope stability due to shear stresses and reducing its resistance. Water pressure and ice segregation enhance shear forces in permafrost rocks [1].

Approach

Two simplified cases of possible rock slopes are to be modelled to account for the ice filled fractures and support the assumptions based on literature. The model is to be built in Swedge, an analysis tool for evaluating the geometry and stability of surface wedges in rock slopes. The goal is to model the ice induced forces as destabilizing forces that could compromise the stability of a specific wedge which can lead to an induce failure of the rock slope.

Finally, a literature study in ice securing measures on rock slopes is presented and safety recommendations are outlined based on the literature reviewed and the outcome of the simplified models.

Conclusions

Rock slopes become unstable driven by changes in temperature and precipitation conditions. Generally, destabilization on rock slopes tends to occur on thawing periods. Hence, critical slope stability results are expected in warm frozen areas where both ice and water are present. Ice might exert certain force on joint rock slopes and induce failure in the jointed rock mass.

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The Effect of Meltwater, Refreezing and Modelled Grain Size on Snow Albedo: Gaining Knowledge from Observations at Weather Stations and Numerical Modelling

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Motivation

The extent to which snow and ice surfaces undergo melt is mainly dictated by their absorption of shortwave radiation, and thus the surface albedo is a critical parameter for accurately modelling the surface energy balance and mass balance of the Greenland Ice Sheet (GrIS). Multiple variables affect the surface albedo, including the atmospheric conditions, solar zenith angle (SZA), and characteristics of the snowpack, such as grain size, shape and orientation; snow depth; and liquid water content.

Whilst accurate models of snow albedo exist at the scale of individual crystals, these cannot be scaled for larger areas, and thus a simplified parameterisation is desired. Many parameterisations employ either Temperature-Dependent or Prognostic schemes, respectively using surface temperatures or albedo decay rates to simulate changes in the snowpack. However, these schemes are not physically-meaningful and subsequently may be specific to certain locations or conditions. This thesis therefore aims to formulate a novel parameterisation for surface albedo that is physically-meaningful and applicable to any time or location by employing a Detailed albedo scheme, which exploits the snowpack's characteristics but remains computationally-feasible enough for inclusion in Regional Climate Models (RCM).

Approach

Shortwave albedo measurements are taken from the Programme for Monitoring the Greenland Ice Sheet (PROMICE; Ahlstrøm et al., 2008), which maintains a network of automatic weather stations (AWS) across the GrIS. These stations provide continuous updates of weather conditions, used here to force a firn evolution model originally developed as a subsurface scheme for the HIRHAM5 RCM by Langen et al. (2015), and subsequently updated by Langen et al. (2017) and Vandecrux et al. (submitted).

The firn model provides an hourly time series of key snowpack variables (e.g. grain size, density, liquid water content), and these variables will be correlated with the AWS-measured albedo to uncover the extent and nature of their contribution. These variables are viewed as either *predictive* variables that will drive albedo variation, or as *segregative* variables that differentiate between separate parameterisation regimes. Additionally, the potential impact of refreezing will be assessed, with meltwater retention, percolation and drainage understood to be an important factor in correctly simulating snow albedo.

Initially, focus will be on the Kangerlussuaq Upper (KAN_U) station in western Greenland (67.0003°N, 47.0253°W). Once a scheme has been developed at KAN_U, it will be tested at other PROMICE sites, and, if time permits, any necessary adaptions these tests reveal will be integrated to the scheme. Finally, the performance of the developed scheme will be compared to existing schemes, such as HIRHAM5's original Temperature-Dependent scheme and an updated Prognostic approach (Nielsen-Englyst, 2015).

Conclusions

Early investigations at the KAN_U station confirm the dominant role of the SZA on diurnal albedo fluctuations. Large inter- and intra-annual variability is apparent in correlations between AWS-measured albedo and snowpack variables from the firn model; work is currently focused on determining whether specific conditions (e.g. extended melt periods, frequent snowfall events) and the SZA can explain this variation. Work to incorporate the effects of cloud cover is also ongoing. It is expected that the developed scheme will be largely driven by grain size and the SZA, modified to account for cloud cover. Contributions from precipitation and melt events are expected to explain more extreme values.

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MSc Thesis: Sustainable Wall Constructions in Arctic Climates

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Motivation

From an engineering point of view, building envelopes have to fulfil two main tasks. These are the creation of a weather-shell that protects the inhabitants from the influences of the changing outdoor-climate-conditions and the establishing of healthy indoor-climate-conditions. Due to the upcoming changes in the Greenlandic building regulation new or adapted envelope types will be required. These will have to fulfil the stricter requirements regarding energy usage. As already described by Tobiasson, there is a need for research on buildings in very cold regions [1].
The aim of this MSc Thesis is to asses five different wall types that meet the upcoming building code and compare them to a typical wall which fulfils the current Greenlandic building regulation. This work is a part of a research project "Development and Testing of Sustainable Envelope and Climatic Systems for New Arctic Building Practice" [2]. The comparison criteria will be hygrothermal properties, economy, buildability, sensitivity towards moisture damage and mold growth.

Approach

Hygrothermal Properties
In the first part the hygrothermal properties of the walls will be investigated. Therefore, the thermal transmittance (U-value) and the vapour permeability of the wall sections will be calculated. This serves the purpose of validating the walls capability to fulfil the upcoming requirements and cope with the water vapour transport. These calculations will include a steady state assessment as well as a transient investigation. Ideally this assessment will allow to validate the theoretical usability of the walls in Arctic climatic conditions, especially for the location of Sisimiut.

Field Test
The second part will be a field study, for which, the wall sections will be built into a test facility similar to the one used by the Cold Climate Housing Research Center [4]. This facility will allow creation of typical indoor climate conditions on the interior while, at the same time, exposing the walls to the climatic conditions of Sisimiut. The sections will be equipped with moisture and temperature sensors to monitor the hygrotehrmal conditions in the critical points inside the structure.

Economics
In the last part the walls will be assessed with regard to their economical sustainability. The cost of a building envelope is basically the sum of transportation-, material-, labour- and maintenance-cost. This cost will be evaluated over the lifetime of the walls with regard to their savings in space heating. Therefore, an adapted version of the method described by S. Petersen and S. Svendsen [3] will be used.

Conclusions

So far only the theoretical assessment of the hygrothermal properties has been performed. All five wall types fulfil the requirements of the upcoming Greenlandic building regulation with regard to their thermal transmittance. However, the vapour permeability in some of the walls bares the risk of internal condensation.

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Repeated Geophysical Surveys of a Destabilized Rock Glacier

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Motivation and Introduction

Rock glaciers have received more attention due to the significant warming on high mountain permafrost in the European Alps, which led to acceleration in permafrost creep (1). Active rock glaciers are creeping permafrost phenomena hence their velocity and mode of movement is correlating to climatic conditions and as a consequence to the ground thermal regime (2). Considering this, temperatures and its changes over time might be regarded as a good proxy for rock glacier velocity changes (3). Rock glaciers can be significant for environmental and construction problems as well as natural hazards (4).

In August 2015 the Lou rock glacier, Maurienne, French Alps, had an active layer detachment which triggered a debris flow that flooded and damaged infrastructure of the village Lanslevillard for up to 100,000 €. The local authorities decided build a dam designed to withstand future debris flows carrying up to 25,000 m3 of debris. The aim of this report is to assess the consistency of the designed dam. This is done by repeated in-situ surveys carried out in August and October 2017 including methods of electrical resistivity tomography (ERT), refraction seismic tomography (RST), UAV photogrammetry and DGPS, aimed to explore relevant geomorphological features.

Approach

The rock glacier Col du Lou has been examined by repeated geophysical surveys to investigate the subsurface and evaluate the future permafrost detachments hazard. Two field surveys were performed in August and October 2017 where ERT measurements was performed at both surveys with a total of five profiles, and one RST profile only in October. In addition, UAV photogrammetry and DGPS geodetic measurements were made for topographic references and to compare with the previous year's survey.

Since mountain permafrost is located beneath thick debris covers, geophysical methods are often used. In this study, ERT and RST are used to explore the internal structure of the rock glacier. Furthermore, in order to estimate the ice content in the soil and thus to determine the complex permafrost structures like rock glaciers, the 4-Phase model was applied. This model, originally developed by the University of Fribourg in Switzerland (5), combines the data of ERT and RST, where respectively the resistivity of the ground and the velocities of the seismic waves are determined. These data make it possible to estimate the fractions of rock, air, water and ice within the medium.

During the surveys several geomorphological factors was investigated; the thickness of the rock glacier, depth of active layer, permafrost content and annual velocity.
Finally three scenarios for a detachment of the active layer are suggested on behalf of the gathered information; one for a similar debris flow to 2015; a model if the whole fast moving part of the rock glacier detach 2-5 meters and in an extreme case, 10 meters; and finally a scenario of a full collapse.

Conclusions

Results of the ERT surveys show the thickness of the rock glacier to be approximately 18-23 meters and from surface to bedrock is consisting permafrost. On behalf of field observations and RST the depth of the active layer was estimated to 2-3 meters, in some areas it might reach 5 meters. The DEM reveals many cracks present on the active part, and the RST substantiates that the cracks are empty. From the DEM the annual movement from 14/09/2016 to 18/10/2017 is found to be up to 4m, which is acceleration compared to the previous years.

By implementing the four-phase model a suggestion of the Ice water and air content was calculated. The model suggests the ice content for the rock glacier to be about 20%. The faction per porosity shows between 45%-65% ice from the surface and to 10 meters depth, from 10-20 meters depth it is 60%-75%, except for the bottom upstream part, which indicates up to 95% ice. The water content shows a uniformly < 10% and in fraction per porosity the middle and downstream part is 20% saturated. The air content in the total fraction shows 0% at the bottom of the rock glacier and as approaching the surface it increases to 20%, only at a few surface anomalies it is seen up to 30%. The air fraction per porosity shows the upper 12m has a content of 30%-50%, and the surface anomalies reaches > 70%. (Figure 1)

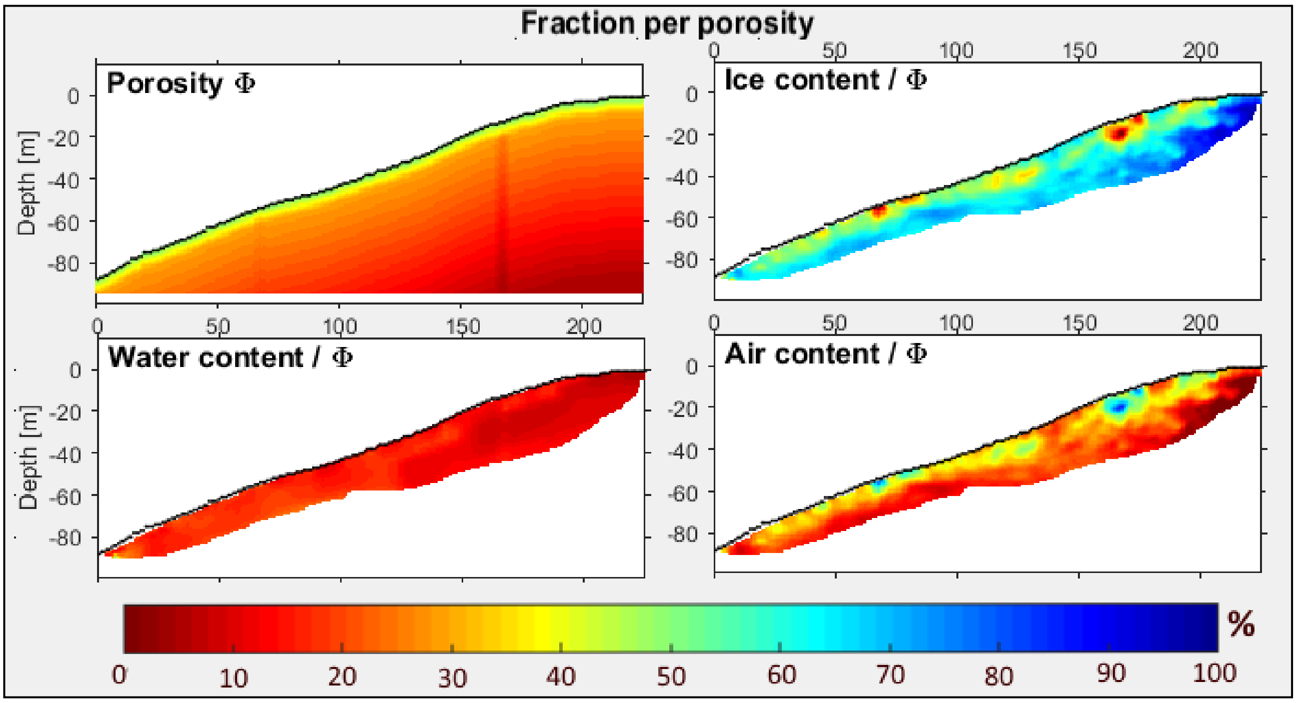

Figure 1. Four-phase model for fraction per porosity carried out by the field survey data

The Risk estimation for the smallest active layer detachment will be 2400 m3, and for an active layer detachment of the whole active part it is suggest to be minimum 19,250 m3 and max 48,125 m3. For a full collapse it is suggested to be 202,125 m3.

It can be concluded that Col du Lou may represent a serious risk for the community. It has high content of ice yet to melt, and the ice appears to be mixed with water. It is revealed that the cracks are empty and may enhance degradation and instability when filled by water in melting or meteoric events. Therefore further monitoring is strongly recommended in order to detect early signs and precluding further destabilization.

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Kangerlussuaaq Airport: Deformations and construction failures in Arctic Permafrost areas

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Background

Infrastructure development is on the hottest topics these days in Greenland, especially for the airports of the country, raising political and media debate about the future of Kangerlussuaq international airport. Kangerlussuaq aerodrome is the main hub and the largest airport in the country. The current technical failures at the pavement, the cost of maintenance and the permafrost conditions are crucial parameters which may play a vitally important role for the future fate of the aerodrome.

Permafrost conditions and Settlements at Western Threshold

The climate at the airport area is stable dry sub-arctic and between 2004 and 2014 the mean annual temperature has been recorded at -3.3ºC. The minimum temperature in the Winter period can reach even -45ºC, while in the Summer up to 25ºC (Menne, 2012). The local area is characterized by continuous permafrost with an estimated thickness at 130m. The Active layer thickness (ALT) is equal to 2m under natural surfaces, whereas at below the paved surfaces it is estimated approximately at 4m (Jørgensen & Ingeman-Nielsen, 2007). The dark asphalt has the ability to absorb the sun radiation resulting in higher temperature below the asphalt and consequently higher ALT values.

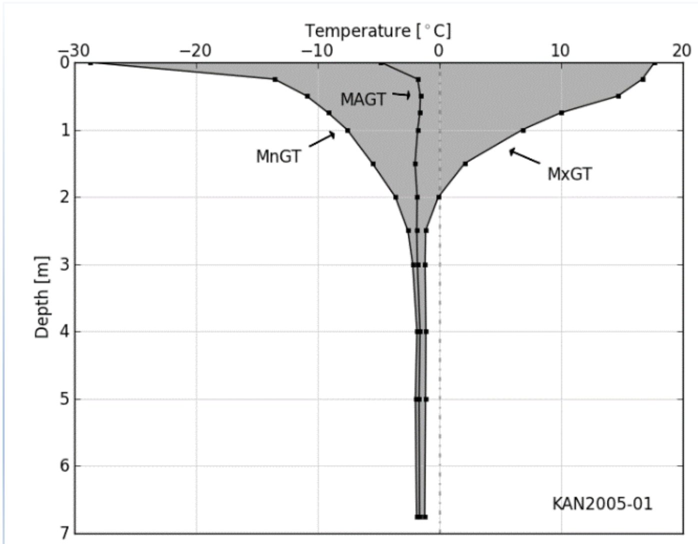

Figure 1: Trumpet curve documenting the thermal regime in natural clay and sandy deposits close to the airport area

In 1973, 15 years after the construction of the runway extension, USAF blueprints document the development of large settlements up to 30 cm of the runway pavement at the western threshold. Local repairs were performed in spring 1973, and during runway repavement in 1988-89, the entire section was excavated and replaced. In 2006, 17 years after reconstructions in the western part (1988-1989), new measurements document additional settlements in the same area. The settlements continue to develop, as documented by repeated measurements in 2011 (Asiaq, 2011). The embankment is about 15 m thick at this location and was constructed in two stages (6 m and 9 m) in an attempt to avoid trapping heat in the embankment construction. The cause of the settlements are presently unknown, but could be related to either constructional issues or the flowing of water through the embankment, causing thawing of the ice rich permafrost below. Restrictions presently apply to this part of the runway, banning usage until damages have been investigated and repaired

Six years later, a group of MSc students carried out an analytical survey making a grid of measurements 10x10m in western part of the runway and 50x50m at the rest of the runway. The results indicated severe settlements equal to 52cm at the western threshold. Figure 2 depicts the progress of the settlements from every measurement that has carried out since the reconstruction of the runway in 1988/89, which is used as a reference considering no settlements that year.

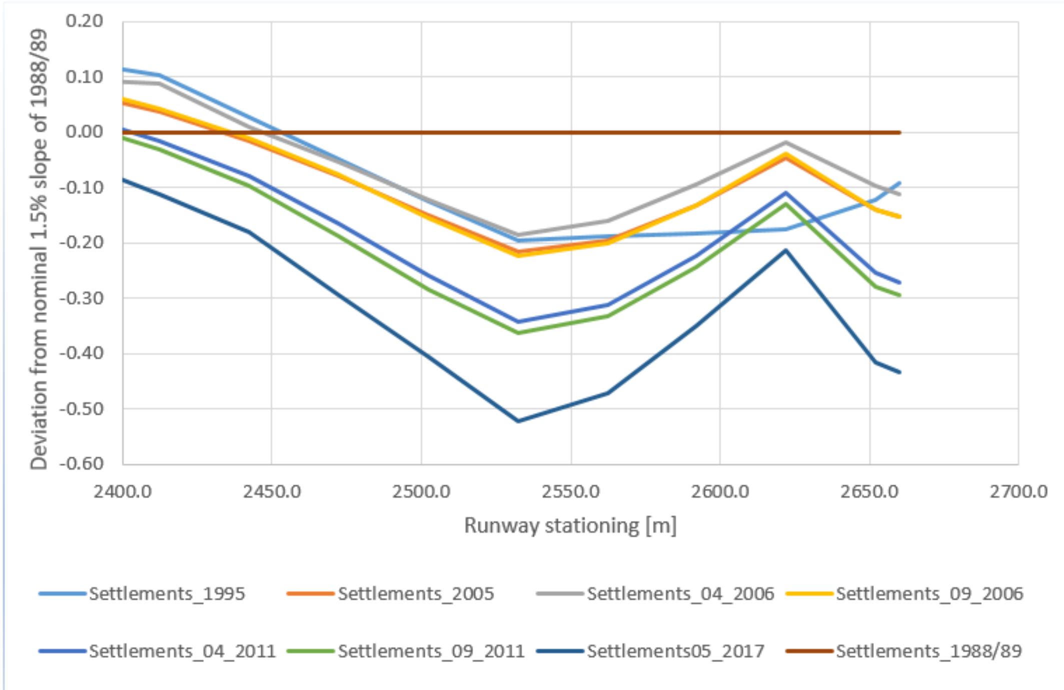

Figure 2: Settlements in the runway center line from 1988/89 to 2017 at the western threshold of Kangerlusuaq airport

Conclusions

The western part of the runway suffers from continuous severe settlements, caused probably by ice rich deposits and non-frost susceptible material used for the construction of the embankment. Another defect observed at the runway pavement is the inadequate and temporary repair of the joints filling with additional concrete. The cracks at the joints are caused probably due to the large thermal variance in the area. The surveying data analysis shows that the maximum annual settlement rate accurs at st. +2532m of the western threshold with an average value of 2.66 cm/year (from 1988/89 to 2017). The increase of settlements the following years could possibly lead to the shortening of the operational area for the airplanes.

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