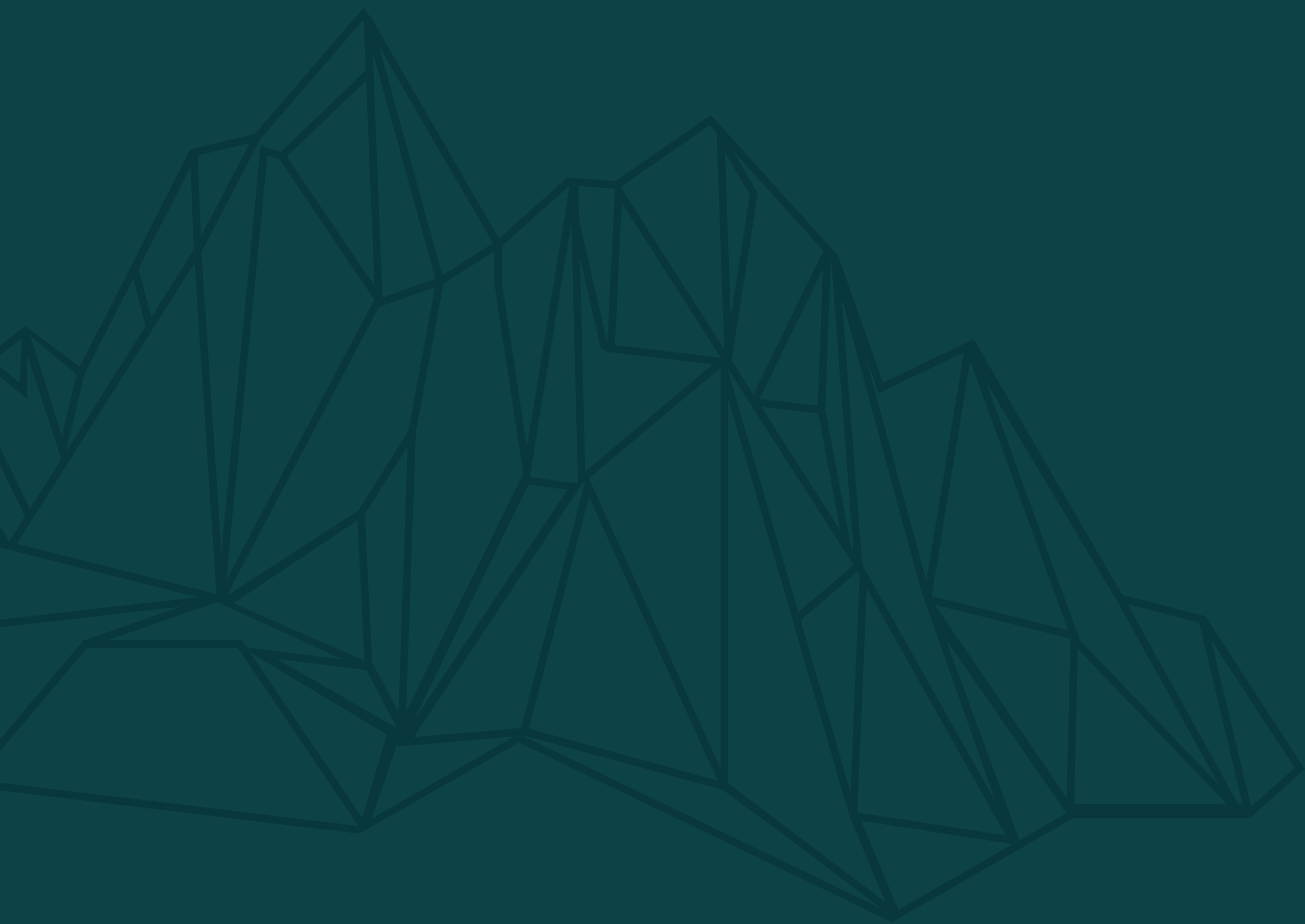
FINAL REPORT 2011-2019

SUSTAINABLE ARCTIC MARINE
AND COASTAL TECHNOLOGY



SAMCoT   sfi   NTNU

SAMCoT KEY FIGURES	2019	2018	2017	2016	2015	2014	2013	2012	2011	Accum.Fig
PhD Defences	4	2	5	4	5	3	3	1	0	27
Published Journal Papers	7	32	10	26	29	16	5	7	7	139
Published Conference Papers	23	33	38	43	52	40	40	18	15	302
MSc Thesis	2	5	5	6	11	6	7	8	2	52
Mass Media & Other Popular Media	0	3	84	36	12	24	11	8	3	181
Industry Partners	8	8	13	13	13	13	11	11	9	8
Research Partners	10	10	8	8	8	8	7	7	7	10
Public Partners	2	2	2	2	2	1	1	1	1	2
PhD Candidates	9 (3)	11 (3)	19 (4)	26 (6)	26 (7)	21 (6)	22 (4)	19 (4)	10 (1)	14
Post Docs	2	5 (0)	9 (0)	9 (2)	9 (2)	4 (1)	3	1	0	2

Partners of SAMCoT.

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www.ntnu.edu/SAMCoT

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FOREWORD

"The journey of a thousand miles begins with a single step". In 2011, SAMCoT had a flying start thanks to the accumulated knowledge and experience from the RCN funded projects PetroArctic and PetroRisk. International recognition, well-established research networks and access to the unique infrastructure situated well into the Arctic region (The University Centre in Svalbard, UNIS, at 78°N) were all key elements in launching SAMCoT. The major events and steps forward in 2011 are outlined below.

The kick-off meeting of SAMCoT took place on 17th March 2011 at the Norwegian University of Science and Technology (NTNU). The overall purpose of the Centre was presented as well as the various research areas. Recommendations and discussions with both industry and research partners formed the basis for quickly starting on the research tasks. To capture the winter season there was no time to lose.

Another major event was the opening ceremony on 7th October 2011. More than 50 people took part in the different events and the official ceremony was followed by the First General Assembly with all SAMCoT partners present.

In the following years SAMCoT continued to pursue its vision to develop key knowledge and innovative tools to promote safe and environmentally sound operations in the Arctic. Several new partners embarked (Exxon-Mobil, SPRS, DTU) and new Associated Projects were developed. The contributions from SPRS and Logistics at UNIS were fundamental to SAMCoT`s field activities and HSE became a key item for all SAMCoT activities, especially those carried out in the field.

In addition to SAMCoT's associated project Ice-induced vibrations of Offshore Structures (IVOS), the Centre continued its extensive collaborative links with different research programmes and organizations. One example is the project "Arctic Ocean 2016". In particular, SAMCoT built a reliable scientific network among other Centres funded by the NRC. SAMCoT's Ice Management and Design Philosophy research group was well established in its collaboration with the Centre for Autonomous Marine Operations and Systems (SFF AMOS). Several PhD candidates at AMOS got field experience from attending SAMCoT research cruises and got acquainted to the Arctic through this collaboration. Another SAMCoT research group, Floating Structures in Ice, did also benefit from the collaboration with the SFI SIMLab and also with the Centre for Integrated Remote Sensing and Forecasting for Arctic Operations (SFI CIRFA).

Details on prizes awarded SAMCoT staff, findings and results from the research can be found in peer-reviewed international journal papers, international conference proceedings and the Annual Reports of SAMCoT from the years 2011-2018. Major inventions and impacts from SAMCoT are presented in this report.

I would like to thank all our partners and collaborators for their continuous involvement and confidence in the vision and importance of the work we all have done at SAMCoT.

Sveinung Løset
SAMCoT Centre Director

Sveinung Løset

Attendees at SAMCoT's first international PhD Workshop in 2012.

Sveinung Løset
SAMCoT Centre Director

SUMMARY

VISION/GOAL:

The vision of the Centre for research-based innovation, Sustainable Arctic Marine and Coastal Technology (SAMCoT) was, from the very beginning in 2011, to be a leading international centre for the development of robust technology needed by industry operating in the Arctic. For this purpose, SAMCoT's goal was to perform research that would aid industry in the environmentally friendly development of the Arctic where unique challenges are presented by ice, frozen soil/permafrost and coastal erosion. In pursuing that goal and in achieving success, SAMCoT is making the host institution, The Norwegian University of Science and Technology (NTNU), a leading international centre in Arctic science and engineering. There are several ways of transferring knowledge to industry. At SAMCoT we believe that this can be best achieved through strong collaboration between academia and industry; e.g. MScs and PhDs bringing their knowledge directly into industry through employment or co-work on specific and relevant tasks.

CONSORTIUM:

The consortium comprises 9 research partners, 12 industry partners and 2 public partners (see the Foreword).

RESEARCH RESULTS/ DISSEMINATION:

The Chair of the Scientific Advisory Committee, Professor Erland Schulson, says: "The overall performance is very good. In addition to the numerous conventional publications (450 international publications), SAMCoT researchers have made significant contributions to ISO standards, specifically to the new 2nd edition of ISO 19906, Arctic Offshore Structures, and to the first edition of ISO 35104, Arctic Operations-Ice Management".

DOCTORAL AND MSC EDUCATION:

A major delivery of SAMCoT is the doctoral and MSc students that have got the opportunity to attend our schools. These schools range from desk studies, seminars, laboratory studies to full scale field surveys including icebreakers. The field surveys range from Pole to Pole with unique data collection and training. From an educational perspective we know that after taking part in such field trips, the students come back with a more realistic view of the Arctic and a better understanding of their research topics. In other words, they become grown-ups.

Impact/innovation: 45 innovation ideas are registered in SAMCoT. From these ideas 3 major commercial inventions are made:

- The Spin-off Company ArcISo;
- A numerical code for assessing ice-induced vibrations of structures;
- A unique Thermo-Hydro-Mechanical constitutive model of frozen soil behaviour.

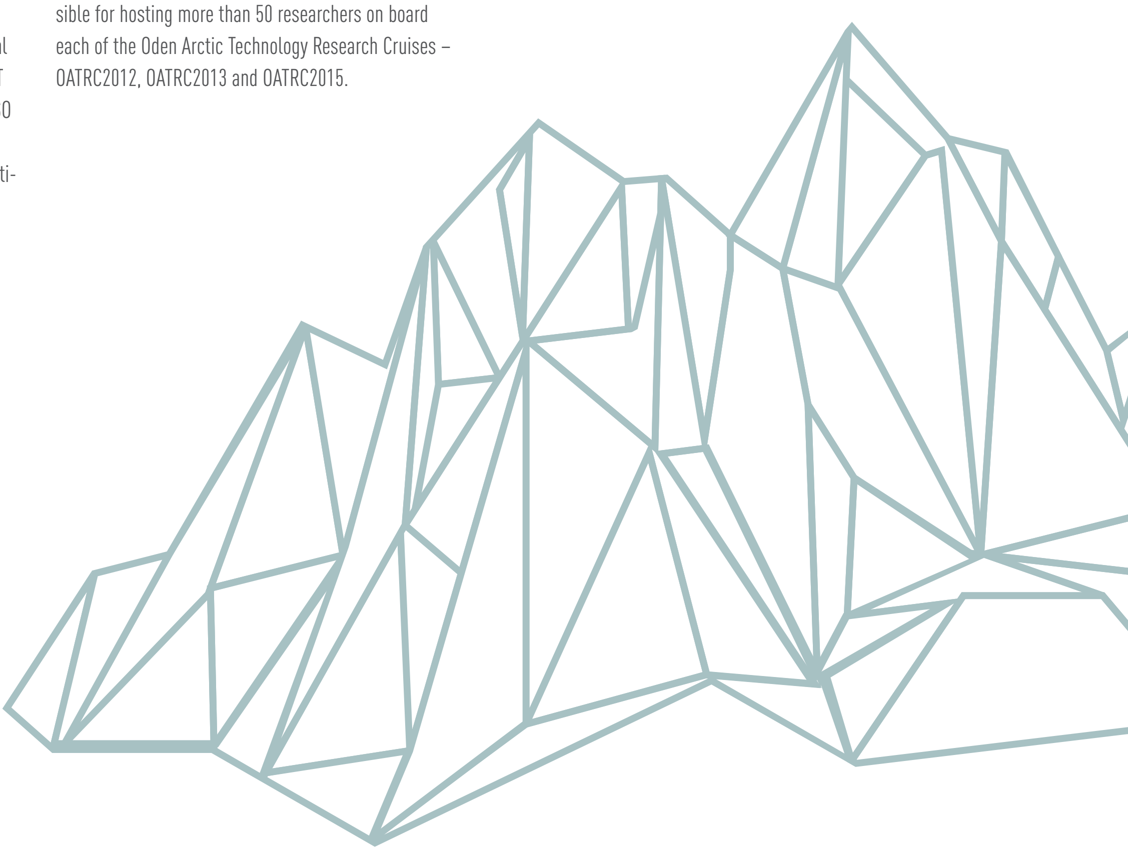
INTERNATIONAL COLLABORATION:

International collaboration throughout the entire life of SAMCoT is well recognised, ranging from collaborators in Canada in the west to Moscow State University in the east. A good example of this is the various research cruises in the Arctic where SAMCoT has been responsible for hosting more than 50 researchers on board each of the Oden Arctic Technology Research Cruises – OATRC2012, OATRC2013 and OATRC2015.

ADDED VALUE BY BEING A CENTRE:

The collaboration between nations and across disciplines in SAMCoT has been visible from the year 2012 when the first major research cruise with the icebreaker Oden took place to the waters East of Greenland. The studies ranged from collecting metocean data to icebreaker performance in ice and acoustic measurements of noise from icebreakers when breaking up ice sheets.
Such dedicated research cruises would never be possible without a broad collaboration as represented by the SAMCoT Centre. Neither would joint efforts to study high coastal erosion rates along the Northern Sea Route be possible with availability of vital temporal data, nor studies of the effects of global warming on thawing of shoreline permafrost and thus contribution to increased erosion.

SAMCoT has been named several times as the Arctic Technology Hub.



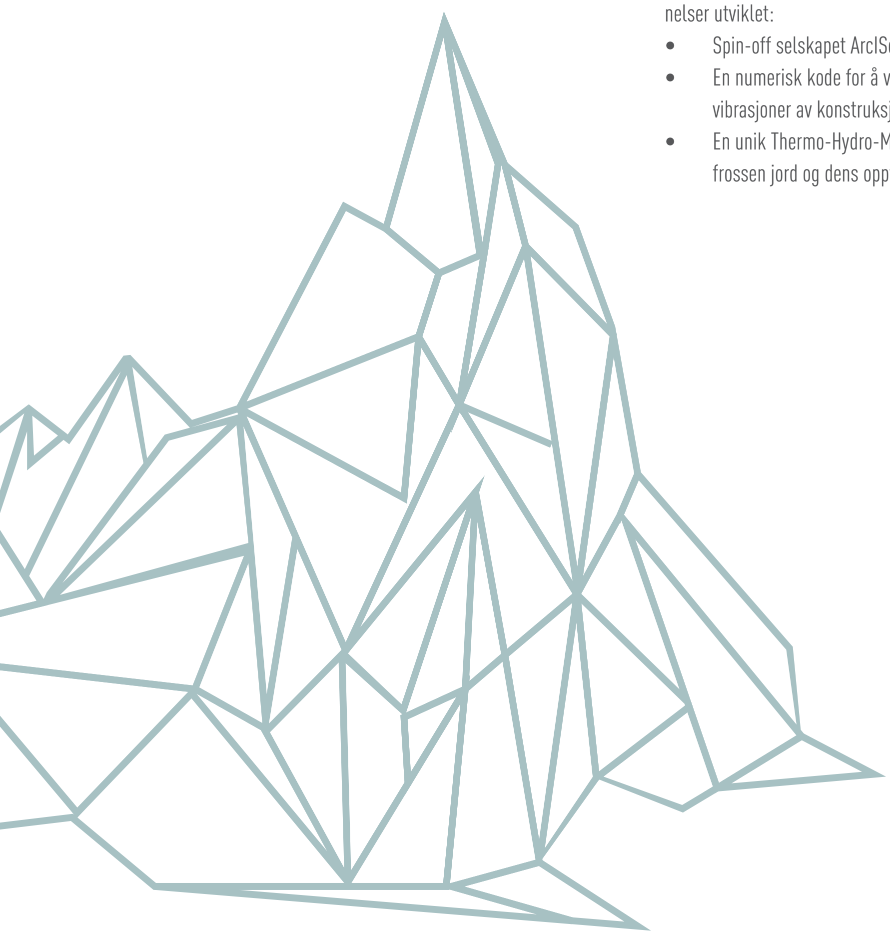
SAMMENDRAG

VISJON/MÅL:

Visjonen for senteret for forsknings-basert innovasjon, Sustainable Arctic Marine and Coastal Technology (SAMCoT) var, helt fra begynnelsen i 2011, det å være et ledende internasjonalt senter for utvikling av robust teknologi som trengs og benyttes av industrien som opererer i Arktis. Her var SAMCoT's mål å utføre forskning som ville hjelpe industrien i miljøvennlig utvikling av Arktis der unike utfordringer er representert av is, frossen jord/permafrost og kysterosjon. Ved å forfølge dette målet og oppnå suksess, er SAMCoT med å gjøre vertsinstitusjonen, Norges teknisk-naturvitenskapelige universitet (NTNU), til et ledende internasjonalt senter for arktisk vitenskap og teknologi. Det er flere måter å overføre kunnskap til industrien på. I SAMCoT tror vi at dette kan best oppnås gjennom sterkt samarbeid mellom akademia og industri; f. eks. bringe master- og doktorgrads studenter sin kunnskap direkte inn i industrien gjennom å bli ansatt der eller gjennom direkte samarbeid på bestemte og relevante oppgaver.

KONSORTIUM:

Konsortiet består av 9 forskningspartnere, 12 industripartnere og 2 offentlige partnere (se forordet).



FORSKNINGSRESULTATER/ FORMIDLING:

Leder av Scientific Advisory Committee, professor Erland Schulson, sier: "den generelle ytelsen er veldig bra. I tillegg til de mange konvensjonelle publikasjonene (450 internasjonale publikasjoner), har forskere i SAMCoT gitt betydelige bidrag til ISO-standarder, spesielt til den nye utgaven av ISO 19906, Arctic offshore Structures, og til den første utgaven av ISO 35104, Arctic Operations-Ice Management ".

DOKTORGRADS- OG MASTER UTDANNING:

En stor leveranse av SAMCoT er doktorgrads- og master studenter som har fått anledning til å delta i vår forskning. Dette spenner fra teoretiske studier, seminarer, laboratoriestudier til fullskala feltundersøkelser inkludert isbrytere. Feltundersøkelsene spenner fra Pole til Pole med unik datainnsamling og opplæring. Fra et pedagogisk perspektiv vet vi at etter å ha deltatt i slike feltstudier, kommer studentene tilbake med et mer realistisk syn på Arktis og en bedre forståelse av hva deres forskning omhandler. Med andre ord, de blir voksne.

Nyskaping/innovasjon: 45 innovasjonsideer er registrert i SAMCoT. Fra disse ideene er 3 kommersielle oppfinnelser utviklet:

- Spin-off selskapet ArcISo;
- En numerisk kode for å vurdere is-indusert vibrasjoner av konstruksjoner;
- En unik Thermo-Hydro-Mekanisk modell av frossen jord og dens oppførsel.

INTERNASJONALT SAMARBEID:

Internasjonalt samarbeid gjennom hele løpetiden til SAMCoT er godt anerkjent, alt fra samarbeidspartnere i Kanada i vest til Moskva State University i øst. Et godt eksempel på dette er de ulike forskningstoktene i Arktis der SAMCoT har tilrettelagt for mer enn 50 forskere om bord hver av toktene med isbryteren Oden (Oden Arctic Technology Research Cruises-OATRC2012, OATRC2013 og OATRC2015).

MERVERDI VED Å VÆRE ET SENTER:

Samarbeidet mellom nasjoner og på tvers av disipliner i SAMCoT har vært synlig fra året 2012 da det største store forskningstoktet med Oden fant sted til farvannene øst for Grønland. Studiene varierte fra innsamling av metocean data til isbrytelytelse i is og akustiske målinger av støy fra isbrytere når de bryter is. Slike dedikerte forskningstokt ville ikke vært mulig uten et bredt samarbeid slik vi har sett det i SAMCoT. Heller ville ikke felles innsats for å studere kyst-erosjon langs den nordlige sjørute (NSR) være mulig uten tilgang på vitale og lokale data gjennom deltakelse av russiske forskere, eller studier av virkningene av global oppvarming på tining av permafrost i kystsona og dermed økt erosjon.

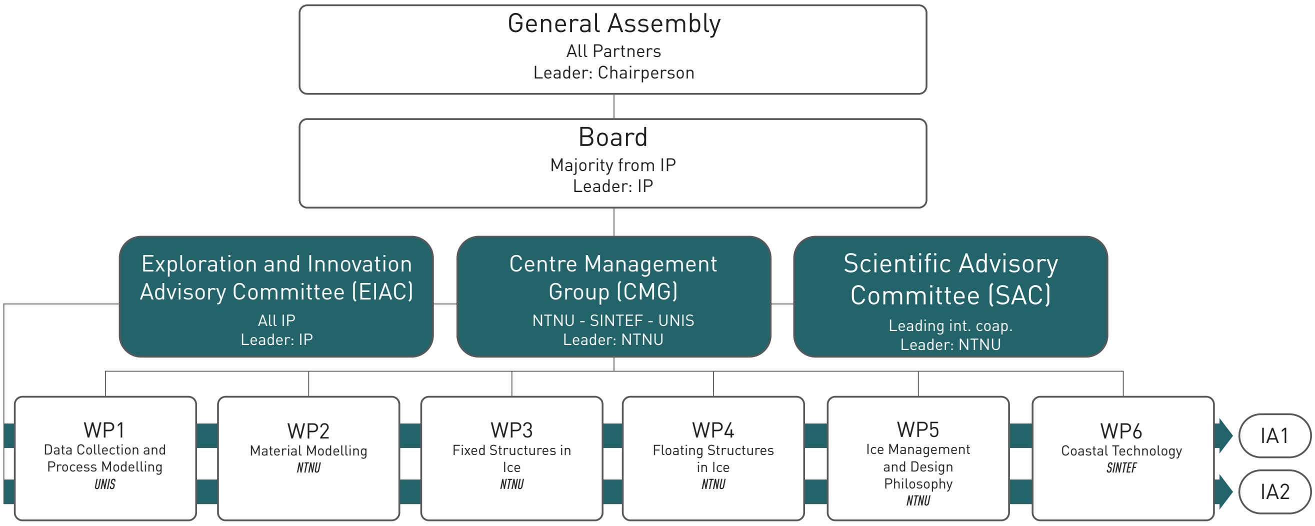
Internasjonalt har SAMCoT ved flere anledninger blitt omtalt som det ledende arktisk-teknologiske navet.

BASIC FACTS ABOUT THE CENTRE

THE GOVERNANCE STRUCTURE OF SAMCoT

The General Assembly (GA) is the ultimate decision-making body of SAMCoT. The Board is a decision-making body that approves and monitors the progress and working plans. The chairperson of the Board has been an Equinor representative throughout.

The work package leaders are members of the Centre Management Group (CMG) which is led by the Centre Manager, Professor Sveinung Løset. The CMG is the operative body for the execution of SAMCoT. NTNU has been the host institution of SAMCoT with UNIS and SINTEF as major research partners. Details of members of the General Assembly, Board and CMG at any given time can be found in the Annual Reports.



The Governance structure of SAMCoT. The leadership of WP6 shifted from SINTEF to NTNU in 2015.

THE STRUCTURE OF SAMCoT

Reliable designs of Arctic offshore and coastal structures require a proper quantification of the physical environment. The relevant properties of ice, soil, water and other environmental characteristics must be described in a mechanical and statistical sense. This competence represents the backbone of SAMCoT and provides part of the basis for the design of Arctic offshore and coastal structures.

From the very beginning SAMCoT was divided into six scientific work packages (WPs):

- **WP1** – Data Collection and Process Modelling: WP1 collects and analyses field data on sea ice, icebergs, currents and coastal permafrost. The primary goal is to provide field data as required by the other WPs.
- **WP2** – Material Modelling: WP2 provides constitutive models for ice rubble (ice ridges) and permafrost that can be used in advanced analyses of boundary value problems in other WPs.
- **WP3** – Fixed Structures in Ice: WP3 focuses on the development of analytical and numerical models to predict the action from ice (first- and multi-year, level ice and ridges) on fixed single and multi-leg structures, and to develop innovative vibration mitigation measures.
- **WP4** – Floating Structures in Ice: The purpose of WP4 is to develop new knowledge, analytical and numerical models to improve the prediction of loads exerted by first/multi-year ice and ridges as well as icebergs on floating structures. This also includes prediction of the performance of the structures.
- **WP5** – Ice Management and Design Philosophy: WP5 is to establish a philosophy that ensures that the Ultimate Limit State (ULS) and Accidental Limit State (ALS) requirements are fulfilled by Arctic offshore structures without being overly conservative. This philosophy considers the use of ice management means such as icebreakers, iceberg towing vessels, structure disconnection and reconnection capabilities.
- **WP6** – Coastal Technology: To develop new knowledge, analytical and numerical models to improve the prediction of coastal erosion in the Arctic. This is essential for the design of environmentally friendly and sustainable coastal structures and technologies, i.e. the knowledge gained in WP6 will provide the bases for design guidelines.

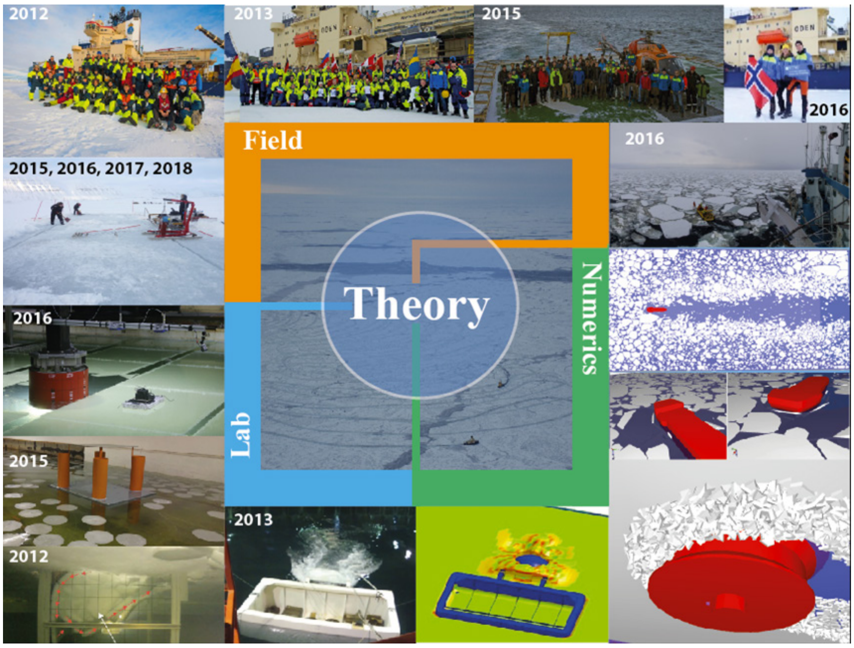
For practical reasons, WP2 was merged with WP3 in 2017.

THE RESEARCH APPROACH OF SAMCoT

The research strategy of SAMCoT is reflected in the figure below. From a hypothesis or theory, we aim to understand the engineering problem by studying the phenomena at full or laboratory scale.

From this research numerical models are developed, calibrated and applied for the benefit of society. A very important part of the efforts in SAMCoT is contributions to relevant education of MSc and PhD students. By linking their education to participation in field and laboratory work and in working with real data, students get first-hand knowledge of some of the challenges and solutions, e.g. in an offshore field development.

To date SAMCoT has delivered 27 PhDs and published 139 papers in international journals and 302 conference papers. Development of numerical models has a very strong focus at SAMCoT.



The research approach of SAMCoT.

SCIENTIFIC ADVISORY COMMITTEE

From the very beginning of SAMCoT a Scientific Advisory Committee (SAC) was established. The committee consists of leading academics, providing the necessary research quality assurance and support to the Board in scientific matters. The SAC has produced annual reports that give an objective view of the scientific quality of the work carried out, as well as following up the educational aspects of SAMCoT.

The proximity of Norway to the emerging new Arctic environment, combined with the long history of NTNU's expertise in engineering, provides essential elements. Just as importantly, if not more so to the high success of the program, is the quality of leadership of each work package and the cohesiveness of the entire team. Measured by the ratio of the level of scientific and engineering accomplishments to the financial resources spent and by recent innovations, this program is truly impressive. It demonstrates that with a consistent focus on the goal from all stakeholders and by each member of the team, extraordinary progress can be made.

Science-based engineering is more than gathering data, analyzing results, creating models and then publishing papers and theses. It is also about people and collegiality. Some years ago, the 2013-14 Fulbright Arctic Chair, Professor Schulson, visited NTNU and for seven months was close to SAMCoT. During that period, he gained a very positive impression of the high quality of both the leaders and the young people engaged in the program and of the degree of interpersonal interaction. Each day, for instance, students, post-docs, visitors and team leaders would gather for lunch in "the basement" - a special place where people young and old and of many nations would come together over a meal, often describing a specific aspect of work in play or, just as often, simply enjoying each other's company.

Photo of the SAC Committee: From left Dr. Steve Bruneau (Memorial University), Prof. Matti Leppäranta (University of Helsinki), Prof. Hayley Shen (Clarkson University), Dr. Robert Frederking (National Research Council Canada), Prof. Erland Schulson (Thayer School of Engineering at Dartmouth College).

To the building of relationships, to the development of all masters and doctoral students who have either now entered the market place or who will shortly, and to all the good work on Arctic Science and Engineering that has been done over the past eight years - a fine legacy indeed - we say: "well done SAMCoT".

EXPLOITATION AND INNOVATION ADVISORY COMMITTEE (EIAC).

The EIAC was established from the very beginning of SAMCoT. At first they influenced the research topics to be prioritized. The EIAC monitors project results with respect to their potential for commercial exploitation and proposes to the GA the further development of such results in separate spin-off innovation projects, EU projects or pre-competitive projects. The EIAC also advises the GA on matters relating to intellectual property rights.

The first chairman of EIAC was Dr. Guido Kuipers (Shell) followed from 2016 by Sigurd Teigen (Equinor).

The EIAC Committee Chair, Dr. Sigurd Teigen (Equinor).

SAMCoT's success in innovation has been achieved by creating opportunities for innovation, which stimulate research in joint and collaborative industrial partner applications, over and above what is possible through their individual development routes.

The EIAC has typically had bi-annual meetings with the Centre Management Group (CMG) in conjunction with the scientific seminar and technical workshops. The EIAC started tracking innovations and exploitations in 2016 (the "harvesting period of SAMCoT") by using an innovation template for the short description of ideas. In total 45 ideas were registered, ranked and prioritized by the EIAC and matured to variable Technology Readiness Levels (TRLs). Full-scale data collection and testing opportunities for technology has been a key to success, and the people and the competence is a major legacy.

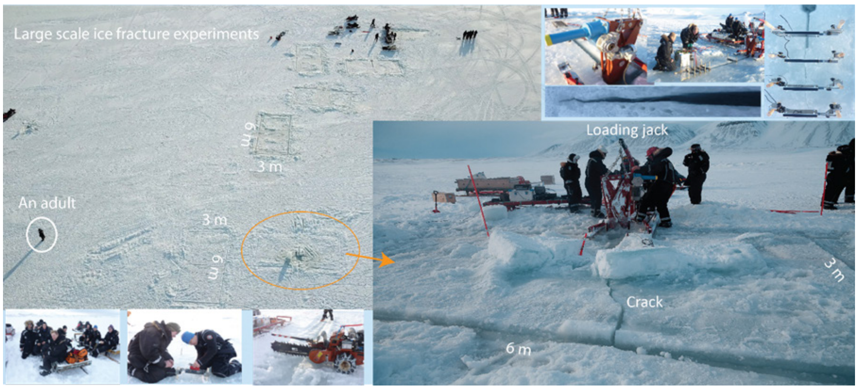
INTERNATIONAL COLLABORATION IN SAMCoT

"One of the important aspects of SAMCoT has been the active international collaboration we have all enjoyed", says Professor Jukka Tuhkuri, Aalto University, Finland. This has included many aspects, from informal workshops and annual seminars to joint field campaigns and papers. SAMCoT allowed our group at Aalto University to continue our work on discrete element modelling of ice mechanics, to share our approach and results, to obtain new ideas and feedback and hopefully to contribute to the goals of SAMCoT. It has been a pleasure to be onboard and it has been a privilege to share ideas, information and workload.

More than ten years ago, while both studying sea ice ridges, we started together with Knut Høyland to arrange NTNU/Aalto workshops where our doctoral students presented their thesis work. We believe that these workshops helped our students to focus and finish their work and gave them collegial support in an environment that was more friendly than an international scientific conference. When we both started to work at SAMCoT we continued these workshops under the SAMCoT umbrella with the title Ice Rubble Workshop. More scientists joined our meetings, more interesting talks were given, and the topic grew to include ice mechanics in general, but the same format was maintained: long presentations were allowed if not requested; critical but constructive discussions were held and lots of coffee was consumed. Now after SAMCoT we are so accustomed to this form international collaboration, that we have agreed to continue the series of Ice Rubble Workshops in the future.

Another SAMCoT activity that turned out to be very important to me was the joint field work we conducted in Svea on Svalbard. At the time Sveinung Løset started discussions about SAMCoT conducting fracture experiments with sea ice, I had agreed with John Dempsey from Clarkson University to join Aalto University during his sabbatical to conduct fracture experiments with freshwater ice. We all then joined forces, shared knowledge, expertise and scientific goals, and succeeded in learning new features of ice fracture. Scientific work is the goal and purpose, but safety always must have priority and that also includes planning times of rest.

International collaboration in SAMCoT has had a number of important outcomes, but if I needed to select the most important it would be this: SAMCoT has educated a group of young scientists who know each other well, who share research interests and who are now faculty members in different European universities. This new generation of scientists in Arctic Marine and Coastal Technology grew up during SAMCoT, have already initiated their own research topics, have obtained funding for joint research projects and will thus take this discipline into the next decades. SAMCoT made this possible. SAMCoT will be remembered as the Center that got them going.



Large scale ice splitting tests.

The level ice splitting test team in 2016, Svea, Svalbard.

INNOVATIONS AND SCIENTIFIC/ENGINEERING IMPACT OF SAMCoT

ARCTIC INTEGRATED SOLUTIONS AS

Arctic Integrated Solutions AS (ArcISo) is a spin-off company from NTNU established in 2016. Its vision is to increase the technology readiness level of SAMCoT's numerical models in order to produce a professional software package for the analysis of sea ice actions and action effects on Arctic offshore and coastal structures. This software package is called Simulator for Arctic Marine Structures (SAMS) and it was first released in 2017.

SAMS is a time-domain simulation product and is largely based on the non-smooth Discrete Element Method (DEM) whose contact algorithm is specifically developed for ice materials. Until recently, time domain models of sufficient quality to perform numerical simulations of ice and marine structure interactions have not existed. Today, this has changed, partly through the efforts of SAMCoT, hosted by NTNU, and laying the foundations for a versatile and accurate numerical simulator for fixed and floating structures in various ice conditions. As continuum-mechanics-based methods are not valid for representing realistic ice conditions in major parts of the Arctic, SAMCoT has placed considerable emphasis on developing DEMs that enable the modelling of interactions between individual ice blocks (e.g., floe ice, level ice, ridges and icebergs) and structures of interest.

ArcISo's impact is easily visible and it manifests itself in several projects that were successfully executed over the past two years as shown below:

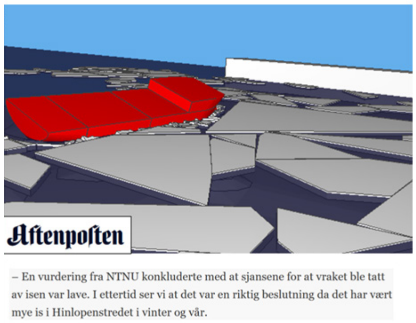
Take for example the story of the trawler "Northguider", which was stranded in Sparreneset in Hinlopenstredet on the 28th December 2018. The accident happened in a very vulnerable area which is sometimes surrounded by drift ice. The Coastal Administration consulted ArcISo to assess the risk of having Northguider pushed by sea ice to deeper waters and thus to advise whether or not a salvage operation could wait until summer when it would be much easier, safer and more economical to operate. Here, the simulator SAMS has been of great use. The ice conditions were thoroughly reviewed, and tens of scenarios were simulated and analysed. This has enriched the situational awareness for all stakeholders enabling decision making; something the Coastal Administration was very grateful for.

Another example is glacial ice features in the Barents Sea. The Petroleum Safety Authority Norway (PSA) considers that floating glacial ice features of various sizes may pose a threat to the structural integrity of man-made structures in the High North. In a competition among several bidders, the PSA awarded ArcISo two projects in 2018 and 2019 to study the complex interactions between glacial ice features, waves, broken sea ice and structures. The lower right figure exemplifies a small iceberg with violent heave motion in waves in the presence of ambient broken ice in the Marginal Ice Zone (MIZ) at Spitsbergenbanken in the Barents Sea. A thorough hydrodynamic analysis of multi-bodies' interactions would yield reliable motion predictions for different sea states.

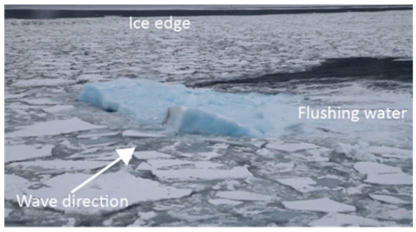
PROJECT	YEAR	CLIENT	ACTIVITIES
FORNY2020	2017-18	RCN	Development and validation of SAMS
NORD ST19	2018	Petroleum Safety Authority Norway (PSA)	Assessment of structural Damage due to Glacial Ice Impact
Wisting Field	2019	OMV	Second opinion ice studies
Northguider	2019	Coastal Administration	Simulation of ice loads
NORD ST20_2019/313	2019	Petroleum Safety Authority Norway (PSA)	Loads, design, operations of floaters in the North

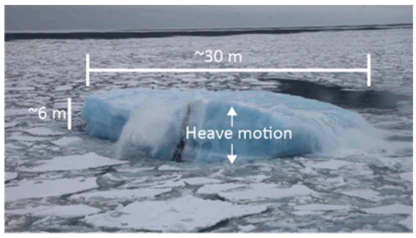

SVALBARDPOSTEN
VERDENS NORDLIGSTE AVIS

Kystverket har fått en utredning fra NTNU som viser at risikoen for at isen skal flytte på havaristen i løpet av vinteren er liten. Den største risikoen er isflak på opptil én kvadratkilometer som driver fra sør, men erfaringen tilsier at disse isflakene forekommer sjelden, og vil passere lenger fra land.


Aftenposten

– En vurdering fra NTNU konkluderte med at sjansene for at vraket ble tatt av isen var lave. I ettertid ser vi at det var en riktig beslutning da det har vært mye is i Hinlopenstredet i vinter og vår.





Small iceberg motion in waves and broken ice in the MIZ around N77.18º and E25.3º (March 2016), Barents Sea.

The motions of the glacial ice features are studied relative to a semi-submersible structure for the designated sea state and in the presence of sea currents, which enabled identification of the impact velocities and hit locations on the structure. The outcomes of these analyses are Probability Density Functions (PDFs) for impact velocities and locations on the structure.

The results of these motion studies are used by SAMS to simulate hundreds of impact scenarios. For each impact scenario, the demand for energy dissipation is calculated, i.e. the fraction of the total impact energy (kinetic energy) that is dissipated at the contact by crushing the glacial ice and deforming the semi-submersible structure. The rest of the impact energy is usually transferred to global rigid-body motions. In 2018, the outcome of this stage is an energy map showing the demand for energy dissipation at each location on the structure. Consequently, one can identify a number of critical impact scenarios that might potentially lead to structural damage.

Current design standards and recommended practice do not provide clear procedures to estimate structural damage due to impact with glacial ice features for the Accidental Limit State (ALS) analysis. Here we adopted the so called shared energy approach by analogy with the procedures for ship-installation impacts (DNV-GL-RP-C208, 2016). For the critical scenarios identified, integrated analyses in LS-DYNA and SAMS are carried out. The former implies a non-linear Finite Element Method (NLFEM) type of analysis that assumes rigid ice and a deformable structure, and it is used to derive force-deformation curves for the structure. The latter (SAMS) assumes a rigid structure and this is used to derive force-deformation curves for the glacial ice features. The combined results are used to define the amount of energy absorbed by the structure and the consequent structural damage in the form of deformation or indentation.

In 2019, the integrated procedures were further refined. SAMS has been upgraded to partially consider the real-time coupling between structural deformation and ice crushing processes. This leads to the direct production of a damage/deformation map around the structure giving a more straightforward illustration of the sensitive locations on the structure.

Given the versatility of the state-of-art simulation tool SAMS and the promising results obtained so far, ArcISo was further commissioned by PSA to summarize the studies and make relevant improvements to the standards Norsok N-300 and N-400. This further emphasizes ArcISo's impact on relevant industries, society and the world.

ICE-INDUCED VIBRATIONS

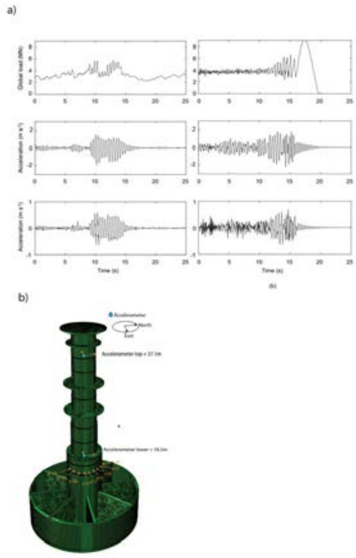
The problem of vertically-sided structures experiencing severe vibrations when level- or floe ice crushes against them has been studied for over five decades since the Cook Inlet oil and gas developments. The research on these ice-induced vibrations in SAMCoT has resulted in a new numerical model which is the first allowing to reproduce full-scale observations of dynamic ice-structure interaction at a high level of detail. The novelty in the model is in the description of local contact and failure during the interaction between ice and structure based on experimental work in the SAMCoT project.

The numerical model has been adopted by the offshore wind industry and verified by DNV-GL for compliance with international design standards such as IEC 61400-3-1 and ISO 19906. Over the past two years this model has been applied in five commercial offshore wind projects both in the initial design phase to obtain insight into the dynamic ice-structure interaction and in the detailed design phase to specify the design ice loads on the structures. Current application areas are the Baltic Sea, for example the Danish Kriegers Flak and Baltic Eagle wind farm, as well as lakes with more moderate ice conditions, for example Windpark Fryslân and the Nissum Bredning Demonstrator project.

The knowledge obtained in SAMCoT has further been applied in the revision of the section on dynamic ice actions in the recent update of the ISO 19906 design standard and is referred to in the recently released IEC 61400-3-1 design standard for fixed offshore wind turbines. Besides these contributions to design practice, the developed model is now at the basis of two European research projects. The FATICE project, studying fatigue in cold regions, which is hosted by NTNU, and the SHIVER project, targeting offshore wind developments in cold regions, hosted by TU Delft. In both projects the SAMCoT researchers continue to collaborate extensively with the aim of increasing knowledge on ice crushing to allow for better optimized and sustainable developments of fixed structures in cold regions.

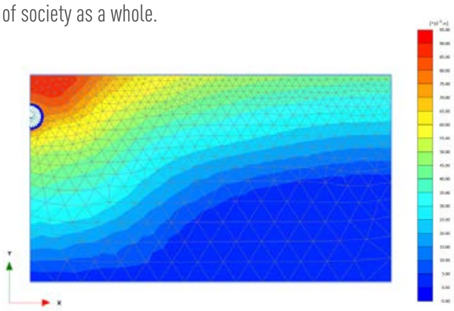
FROZEN SOIL BEHAVIOUR

The topic of frozen soil is of great interest to the civil engineering industry in cold regions. For instance, in the European Union the cost of maintenance and rehabilitation of pavement structures due to winter conditions is about 245 million Euros per year, based on 2000-2010 data. Thus, SAMCoT put considerable effort on this topic by appointing a postdoc, Seyed Ali Ghoreishian Amiri. He developed a unique thermo-hydro-mechanical constitutive model that represents many fundamental features of frozen soil behaviour, including frost heave and thawing settlements. The figure to the right shows an example of the frost heave phenomenon around a chilled pipeline simulated by this model.
Frost heave and thawing settlements are sources of specific danger to infrastructures in cold regions. The problem relates to the fact that in fine-grained soils unfrozen water can exist at temperatures down to -70°C with cryogenic suction and other effects as a consequence. It results in dramatic water migration to the freezing fringe during a freezing period. The additional water must subsequently be drained out of the system during the thawing period. This water migration and drainage results in significant deformation of the soil system (frost heave and thawing settlement) and consequently it may cause serious damage to the infrastructure above. The model drew the attention of a commercial software company "Plaxis" (https://www.Plaxis.com/support/models/frozen-and-unfrozen-soil-model/). It is now implemented in their software and receives worldwide exposure in this specific field to the benefit of society as a whole.



a) Measured vs. b) modelled global loads and responses using the simulation model coupled to a FE representation of the Norstrømsgrund Lighthouse.

Offshore wind developments where the SAMCoT model for dynamic ice-structure interaction has been applied to gain insight and define the design ice loads. (source of map: 4C Offshore).



Deformation profile around a chilled pipeline due to the frost-heave phenomenon.

WP1

DATA COLLECTION AND PROCESS MODELLING

WP1 "Data Collection and Process Modelling" performed activities in the following fields:

1. Sea state and ice conditions in the Barents Sea and Svalbard region
2. Physical-mechanical properties of ice and frozen soils
3. Ice and water actions in coastal zones
4. Applied oceanography and navigation
5. GI system - Performance and data storage

The work performed by WP1 includes design and construction of equipment for field and laboratory work, field and laboratory investigations, data processing, mathematical modelling and numerical simulations. Field work on an annual basis was performed in March (2012-2019) on land-fast ice of the Van Mijen Fjord near Svea in Spitsbergen, in April (2012-2019) on drift ice in the NorthWest Barents Sea, and in October (2011-2018) on the fresh water lake ice near Longyearbyen. Long term in-situ measurements of sea currents, velocities and waves were performed near the research site for the monitoring of coastal erosion in the Ice Fjord (2012-2013) and in the navigational strait Akselsundet in the Van Mijen Fjord (2015-2016) in Spitsbergen. Long term in-situ measurements of ice temperature and ice pressure on the sheet piling of the coal quay in Kapp-Amsterdam in the Van Mijen Fjord of Spitsbergen were performed between 2013 and 2015. WP1 participated in the organisation of the field works on Varandey research site in 2012-2013. A. Shestov participated in the Norwegian Young Sea Ice expedition (N-ICE2015) from January 11 to June 23, 2015. The expedition was onboard the RV Lance frozen in the drift ice in the west sector of the Arctic Ocean drifting to the Fram Strait.

Original rigs for in-situ investigation of the mechanical characteristics of ice at small and medium scales were designed, constructed and used in the field campaigns on land-fast sea ice, drifting sea ice and fresh water lake ice. The equipment for large scale tests was constructed by MK Lund Company (Oslo) and designed together with researchers from Krylov State Research Center (St. Petersburg). The method of conducting medium scale tests on compressive, tensile, indentation and flexural strength was elaborated and introduced in practical field investigations of ice properties. A system of fiber-optic strain and temperature sensors was designed for laboratory measurements of ice properties in close cooperation with Advance Optics Solutions GmbH (Dresden) and used to investigate the mechanical behavior of ice and frozen soils under thermal loading.

During the field works in the Barents Sea, 28 ice tracking buoys were deployed on drifting floes and icebergs. The ice trackers transmitted the data on their geographical positions via Iridium with a sampling interval of 10-20 minutes. Some of the trackers were equipped with thermistor-strings to measure ice temperature, anemometers to measure wind velocity near the ice surface and accelerometers to measure floe accelerations. The data collected were used to reconstruct the shapes of sea ice and iceberg drift trajectories, the velocities of sea ice and iceberg drift, the spectra of ice drift velocities, the wind drag force on drifting ice and wave characteristics in the marginal ice zone of the Barents Sea.

It was discovered that ice trackers deployed near the ice edge follow the boundary of the ice edge. The trajectories of the ice trackers have many loops, and each of the loops is passed by the tracker over one semidiurnal cycle. The maximum speed of ice drift is reached on the ice tracker trajectories with the smallest curvature. The maximum speed of drifting floes was measured above 1.5 m/s in the North West Barents Sea. Increasing the sampling interval of the GPS positions on the ice trackers from 10 min to 6 hours influences a reduction in the maximum drift speed by approximately 20%. The maximum measured speed of ice drift was registered in the strait Heleysundet and exceeded 5 m/s. Ice trackers deployed on drifting icebergs showed their rotation relative to the vertical axis. The dominant direction of the rotation was clockwise.

Field campaigns on drifting ice included measurements of the ice thickness, measurements of temperature and salinity, drilling studies on ice ridges, laser scanning of the ice surface, small and medium scale measurements of ice strength, measurements of water velocities below the drift ice and temperature and salinity profiling (CTD) over the entire water column. Usually the thickness of level ice formed by water freezing in the Barents Sea is around 0.6 m or less, whereas the thickness of land-fast ice near glaciers can exceed 1 m and the thickness of ice rubble formed due to mechanical processes can be much greater. An extremely large ice rubble field was discovered in May 2016 on the east coast of Edge Island near the glacier Stonebreen. The floating ice rubble field extended over tens of kilometers along the marine boundary of the land-fast ice; its height relative to the water level reached 4 m. Completely consolidated ice ridges due to drifting were discovered and investigated on Spitsbergen Bank almost up to Bjørnøya. The maximum vertical size of the ice ridges was below 10 m and their diameter in the horizontal direction was usually below 30 m. The ice ridges had a salinity of 4-6 ppt and their temperature around the end of April to the beginning of May was close to freezing point. Masses of the investigated ice ridges were estimated to be below 5000 t. These ice ridges present significant danger to navigation in the region between Spitsbergen and Bjørnøya.

Measurements in the boundary layer below drifting ice showed that the heat flux from the ocean to the ice does no exceed 10 W/m^2 in the region between Spitsbergen and Bjørnøya and the eddy viscosity reaches 100-150 cm^2/s in Olga Basin of the North -West Barents Sea. The ocean heat flux influences ice melting from below. In the application the melting of ice ridges melt water inside ridge keels and form frazil ice there. These processes may lead to complete consolidation of ridge keels and may explain the structure of consolidated ice ridges observed on Spitsbergen Bank. The high eddy viscosity in the boundary layer adjacent to the ice is explained by the generation of turbulence below the ice drifting under the influence of wind and sea currents. The turbulent characteristics of the ice-adjacent water layer are important for damping wave energy below the drift ice.

Measurements of wave characteristics were performed by several methods including the measurement of floe accelerations with IMU, the synchronous measurement of water pressure at two different depths below the drift ice, high frequency measurements of water velocity below the drift ice with an Acoustic Doppler Velocimeter (ADV) and the analysis of polarized SAR images of the drift ice at high resolution. It was discovered that the typical period of swell waves observed in the marginal ice zone of the Barents Sea is 10-12 s and the representative distance of the wave damping is around 10 km. The wave damping can be very small in dispersed ice consisting of small floes, but as soon as waves penetrate more compacted ice their damping becomes evident. It was discovered that waves can effectively propagate into ice covered regions of the Barents Sea along the leads formed by ice divergence, but their energy dropped immediately after the closing of the leads due to the ice convergence.

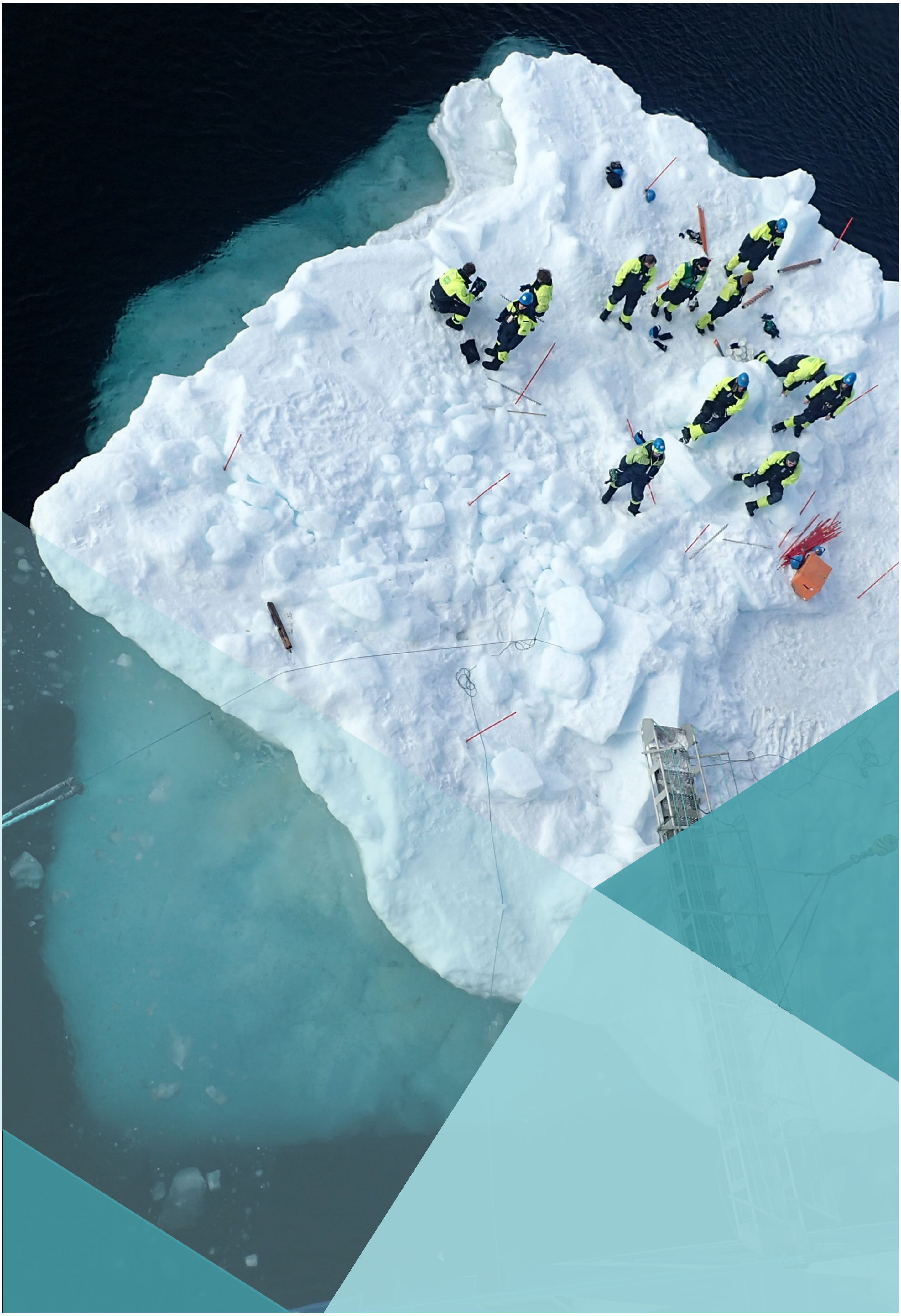
Mathematical models of thermodynamic consolidation of ice ridges were elaborated to describe three physical mechanisms of the consolidation due to atmospheric cooling, penetration of melt water inside unfrozen ice rubble and melting of ice ridge keels from below. It was shown that atmospheric cooling influences the growth of the consolidated layer until its thickness reaches a critical value which is 1.5-2 times greater than the thickness of level ice formed under the same weather conditions. After that the growth rate of the consolidated layer becomes very small. This estimate is valid when the initial macro-porosity of the ice rubble is greater than 20%. Thus, atmospheric cooling cannot explain the formation of completely consolidated ice ridges. Numerical simulations showed that the other two processes may influence complete consolidation of ice ridges. The time to complete consolidation is determined by the initial macro-porosity of ice rubble, the characteristics of melt water penetrating inside the rubble and the ocean heat flux.

A mathematical model of wave damping below the ice was elaborated using the conception of the oscillating boundary layer (Stokes boundary layer) below the drift ice. The characteristics of the boundary are determined in the model by two parameters: the eddy viscosity of water below the ice and the amplitude ratio of the horizontal velocities of the floes and water particles initiated by the wave. The wave damping is associated with energy dissipation in the oscillating boundary layer. According to the model, in the cases when the floe motion is identical to the motion of the water particles (dispersed ice with floe sizes much smaller than the wave length), the dissipation and wave damping are very small. In the case where the ice is compacted, the floe motion initiated by the propagating wave occurs mainly in the vertical direction and wave damping becomes stronger. An eddy viscosity of 100-150 cm^2/s was used

in the numerical simulations of wave propagation in the marginal ice zone of the Barents Sea. The results of numerical simulations of the spatial evolution of wave spectra showed similar characteristics between the modelled and observed spectra.

Small- and medium-scale tests have been performed on floating ice to investigate scale effects and the influence of the temperature, salinity and granular structure on ice strength. All together 7 tests on uniaxial compression, 8 tests on compression with fixed ends beams, 7 tests on uniaxial tension, 16 tests on indentation, and more than 80 tests with cantilever beams were performed at medium scale with floating ice. In the medium scale tests, the load applied to the ice by a rig is distributed over the entire ice thickness. The number of small-scale tests carried out was much larger. Experiments performed on the land-fast ice in Spitsbergen fjords and drifting ice in the North -West Barents Sea demonstrated that the properties of sea ice in these two regions were similar. Comparison of the tests on uniaxial compression with those on the brittle failure of ice demonstrated the absence of scale effect when the size of ice samples changed from 10 cm to 1 m scale under the same liquid brine content of the ice samples and strain rates of 10^{-3} – 10^{-4} s^{-1}. The compressive strength was in the range of 1-2 MPa when the ice temperature was above -5^{o}C. Tests with fixed ends beams demonstrated a compressive strength twice as high, and a decrease of grain sizes in the compression zone after the test. Indentation tests showed even higher strength which is explained by the lateral confinement of ice near the indenter. A decrease of grain sizes in the compression zone was also registered in the indentation tests. It was discovered that the strain rate in the indentation tests was very sensitive to surface vibrations applied by a vibrating plate before the ice was subjected to the action of a cylindrical indenter. The indentation rate increased significantly after the action of the vibrating plate on the ice. WP1 has always emphasized the importance of the storage and processing of collected data and has created a special Geographical Information System (GIS) to optimise utilization and presentation of environmental data. SAMCoT GIS, incorporating WP1 data has been developed since 2012, using ESRI ArcGIS software by N. Marchenko. It shows the important natural environment features of the investigated territory (Svalbard and surrounding seas) such as bathymetry and topography, hydrology and glaciers and erosion. It also demonstrates installed equipment and data obtained during field work (ice trackers, CTD, ADCP, places of field work and corresponding reports). The SAMCoT GIS online was created in 2017 and tested by SAMCoT partners. It makes the data easily accessible from WP1 surveys from research vessels and ice trackers. Data collected by WP1 in 2011-2018 was structured and stored on the SAMCoT server according to guidelines. In addition to the data presented in SAMCoT GIS online, there are folders with sea ice observation, sea ice drift, laser scanning, field investigation at Baydara bay site and ADCP measurements at Vestpynten site. The total volume is more than 600 GB.

Visiting researchers from Russia (Krylov State Research Center, St. Petersburg; Lomonosov Moscow State University; Peter the Great St. Petersburg Polytechnic University; Shirshov Institute of Oceanology of RAS, Moscow), Canada (Memorial University of Newfoundland), UK (University College of London) and USA (Dartmouth College; University of Alaska; CRREL) were involved in the field campaigns over the project period. Researchers from WP1 have published more than 40 journal papers and 70 conference papers since 2012. 21 MSc projects were undertaken at UNIS base. The leader of WP1 Prof. A. Marchenko organized a workshop "Ice-Structure Interaction" at Cambridge University within the programme "Mathematics of Sea Ice Phenomena" at The Isaac Newton Institute of Applied Mathematics in November 2017, and was co-editor of a special volume, "Hydrodynamics of Sea Ice", of the journal Applied Ocean Research which was published in 2019.



WP2 MATERIAL MODELLING

WP2 had two main objectives: a) to address ice rubble (the unconsolidated layer in first-year ridges) and b) to study thermo-mechanical modelling of frozen soils. It was one of the two fundamental WPs giving input to some of the other more applied WPs in the second half of the Centre's eight-year lifespan. WP2 was closed in 2016 and the results were applied further in WPs 3 and 6.

The WP addressed laboratory-scale experiments at NTNU and UCL, numerical modelling with FEM at NTNU and Discrete Element modelling (DEM) at Aalto. Field work was conducted in collaboration with WP1 at Svalbard, in the Barents Sea and in the Fram Strait. The WP had two activities spanning three different countries and five different institutions (NTNU, Aalto, UNIS, UCL and VTT). We organized the "Ice Rubble Workshop" twice each year to facilitate collaboration between the PhD students and post-docs at the different universities. These workshops were also attended by some of the industry partners (Total, Multiconsult and Kværner) who found these academic discussions interesting and useful.

The RITAS campaign was an EU Hydralab project and an associated SAMCoT project led by Multiconsult (at the time Barlindhaug Consult) and co-led by NTNU. Basin-scale experiments were performed at the Hamburg Ship Model basin (HSVA), and the action and accumulation of ice on structures with inclined walls was investigated together with ice rubble properties. This campaign resulted in 8 papers in POAC 2013 and valuable data that has been applied in the validation of numerical routines by both Multiconsult and NTNU.

Sergey Kulyakhtin, Anna Pustogovar and Arttu Polojärvi from Aalto all addressed experimental and numerical modelling of ice rubble. Together they performed experiments with a shear box in the NTNU ice laboratory and compared experimental results with Polojärvi's DEM. They showed how force-chains govern the response of experiments on this scale (Illustrated in the Figure below.)

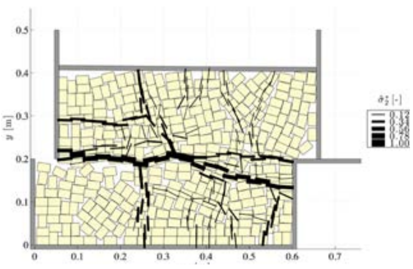


Illustration of Force chains in ice rubble experiments.

Arttu Polojärvi from Aalto defended his PhD thesis in 2012 and then became a SAMCoT post-doc and continued to develop Aalto's DEM model. He studied the two cases of punch tests and shear box tests. After concluding his SAMCoT post-doc he became Assistant Professor at Aalto and continued his research on the numerical modelling of ice ridges and ice mechanics. Among many other activities, he was co-supervisor of the SAMCoT PhD student Janne Ranta in WP3.

Sergey Kulyakhtin's main topic was numerical modelling, but he also conducted several experimental campaigns in the NTNU ice lab and with the EU Hydralab project RITAS at HSVA organised by Multiconsult and NTNU. He also joined the Oden 2012 expedition in the FRAM Strait (associated SAMCoT project sponsored by Equinor). He developed his own numerical FEM model where he expanded the well know Modified Cam-Clay model developed for soils for the concept of breakage mechanics and validated his numerical tool towards the RITAS data.

Anna Pustogovar`s main interest was experimental work and, as shown below, she collaborated with Kulyakhtin and Polojärvi. She was especially interested in measurement uncertainties and developed and published an improved way of conducting ice density measurements. She showed how predictions could be considerably improved and the research group at NTNU and UNIS have adopted this method.

Yared Bekele was developing an advanced theoretical-numerical model for the prediction of the thermo-hydro-mechanical behaviour of frozen soil. He used an advanced integration technique allowing for the coupling of the equations despite the strong discontinuities introduced by phase changes (freezing and melting). His work was taken over by WP6 and developed further.

WP3 FIXED STRUCTURES IN ICE

Work package 3 deals with Fixed structures in ice and has two research areas. Ice-induced vibrations and Ice ridge and rubble accumulation, WP3 was led by Professor Knut V. Høyland.

The Ice-Induced Vibrations (IIV) team was led by Professor Andrei Metrikine (TU-Delft) and consisted of Professor Emeritus Mauri M Määttänen (Aalto), Professor Ole Øiseth, Assistant Professor Eliz-Mari Lourens (TU-Delft), PhD candidate and later post-docs Torodd Nord and Hayo Hendrikse (TU-Delft).

The activity started with the EU Hydralab project Deciphering Ice Induced Vibrations (DIIV) at Hamburg Ship model basin (HSVA) in August 2011 and with the employment of Torodd Nord. In the campaign the mass and stiffness of the structure could be changed and both force-controlled tests and velocity-controlled tests were conducted.

Torodd Nord was the first PhD candidate, appointed in June 2011 and joined the DIIV experiments. His topic was IIV and the analysis of measurements. He started with the DIIV data and continued with full-scale data from the Norströmsgrund lighthouse ,30 km off Luleå in Sweden. These data were collected by the EU projects LOLEIF (Validation of Low Level Ice Forces on Coastal Structures) and STRICE (1997-2003) (Measurements of structures in ice) where HSVA, NTNU and Aalto were members. Torodd was also teaching Ice mechanics at UNIS, firstly as part of his PhD teaching duties and later as an Adjunct Associate Professor. In August 2019 he was appointed Associate Professor in the Department of Ocean Operations and Civil Engineering at NTNU.

Hayo Hendrikse was a PhD candidate and later post-doc at TU-Delft. He worked with the numerical modelling of IIV and created the first model that was able to handle all three acknowledged regimes in IIV. The numerical model was first validated against basin tests from HSVA and later against the full-scale data from Norströmsgrund lighthouse. Hayo joined field work several times and his thesis was rewarded with the distinction of cum laude,

Within WP3, HSVA organised an associated project IVOS (Ice-induced vibrations of offshore structures) allowing for an extended test campaign supporting the PhD work of Gesa Ziemer.

The collaboration between NTNU, TU-Delft and HSVA resulted in the European Commission "MarTERA" funded project FATICE (Fatigue Damage from Dynamic Ice Action, 2018-2021) addressing ice-induced fatigue damage of fixed structures. The project group consists of the SAMCoT researchers Knut Høyland, Torodd Nord, Hayo Hendrikse and includes the Technical University of Hamburg (TUHH). This project has enabled the direct continuation of the research activities and application of the SAMCoT results.

The ice ridge action and rubble accumulation activities began when WP2 closed, allowing the Ice Rubble Workshops to continue. The team consisted of Professor Knut V. Høyland, Professor Jukka Tuhkuri (Aalto), Professor Peter Sammonds (UCL), Professor Aleksey Marchenko (UNIS), Dr. Jaakko Heinonen (VTT), Assistant Professor Artu Polojärvi (Aalto) and PhD students Mark Shortt (UCL), Åse Ervik, Janne Ranta (Aalto), Evgenii Salganik and Ilija Samardzjia.

WP3 PhD candidate Mark Shortt started his work in WP2 and transferred to WP3. He studies the physics of freeze-bonds, an essential feature of ice ridges. His work spans several scales, from small-scale Scanning Electron Microscope work in the laboratory at UCL (University College London) to full-scale experiments in collaboration with WP1 in Svea on Svalbard.

Åse Ervik took leave from Multiconsult in Tromsø to complete a PhD on ice ridge action on structures. Her work consisted of three parts: numerical FE (Finite Elemente) simulations; analysis of full-scale data from Norströmsgrund lighthouse and field work within the N-ICE (Norwegian Young sea ICE cruise) project organized by the Norwegian Polar Institute. SAMCoT's contribution to N-ICE was a joint effort between WP1 and WP3. Aleksey Shestov and Åse Ervik both spent six weeks on the research vessel Lance drifting in the Arctic drift ice while measuring the properties of decaying ice ridges. defended her thesis on 14 June 2019.

Evgenii Salganik's PhD topic was scale-model testing, and he chose to study how ridge consolidation is governed on spatial and temporal scales. He combined medium-scale in-situ field work in Svalbard, small-scale laboratory work at NTNU, basin-scale experiments in Aalto and numerical analysis. Evgenii spent one semester at UNIS and subsequently helps with the UNIS teaching each year.

Ilija Samardzjia's PhD topic was engineering models for ice ridge action on structures, and he chose to develop probabilistic methods. He made an overall framework for probabilistic ice ridge action where he combines physical insight and statistical analysis. He was helping with the teaching at UNIS each autumn and joined the Equinor Station Keeping Trials in the Baltic during the spring of 2017.

WP4 FLOATING STRUCTURES IN ICE

The goals of the research area Floating Structures on Ice have been to develop new knowledge, analytical and numerical models for floaters in ice needed by the industry to improve the prediction of loads exerted by first-year and multi-year level ice and ridges as well as icebergs on floating structures. Further, to predict the structures' performance in various ice conditions. This aim has been the same from the very beginning of SAMCoT, but the way of reaching them has changed somewhat due to changing boundary conditions and opportunities along the course.

One of these opportunities has been to recruit former PhD students into post doc positions where they can cultivate their knowledge further and SAMCoT can harvest on increased knowledge and publications. This has also been done in combination with increased innovation and spin-off strategies.

From an engineering point of view we can split these ice actions between global and local actions on a structure.

GLOBAL ICE ACTIONS

This research area is defined as theoretical and numerical studies of sea ice fracture. Fracture of sea ice is a common load releasing mechanism in the interaction between structures and sea ice. In particular this phenomena has been studied by Dr. Wenjun Lu. .

As part of the basis for including the role of fracture in the global ice actions on offshore structures, the 3rd round of field campaign in the very beginning of 2018 was in the field on sea ice in Svea, Svalbard. The purpose was to retrieve the fracture properties of sea ice. Several large ice floes were cut and fractured. In this round of the campaign, we varied the orientation of the ice floe to investigate if the c-axis of sea ice has an impact on the global splitting force and the fracture properties of sea ice. The figure to the right shows several ice floes, with different orientations, that were tested.

In this test campaign, the so-called kink tests were also performed to study the crack path during ice fracturing. This has a direct impact to the application of ice management operations, in which, long cracks were kinked in between parallel channels. Related numerical simulations with the developed XFEM code has also been conducted.

In several of the tests we were able to capture the fracture zone at the crack tip. Some samples were brought back to the cold lab at UNIS for microstructure analysis of these samples as can be seen in the figure on the next page.

Fracture tests of ice floes with different orientations.

Kink tests (a drone view from above showing the crack path highlighted with red markers)

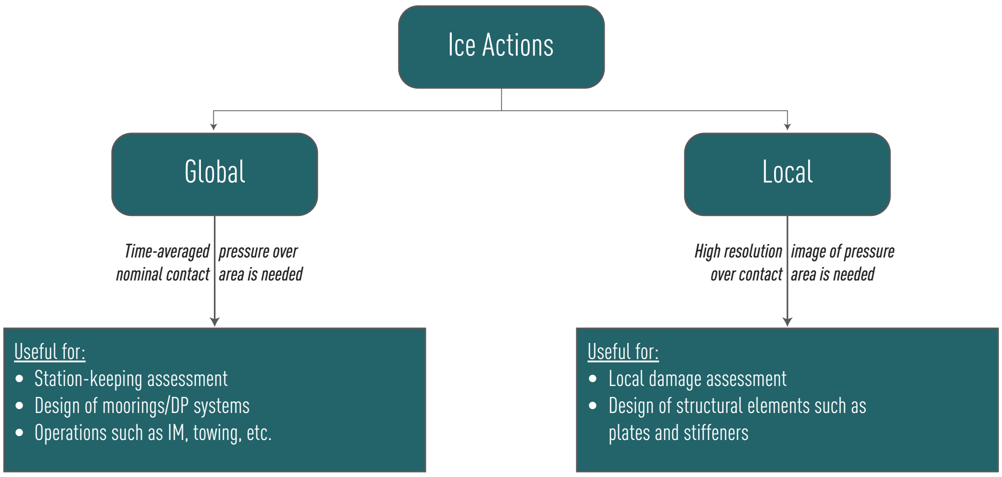
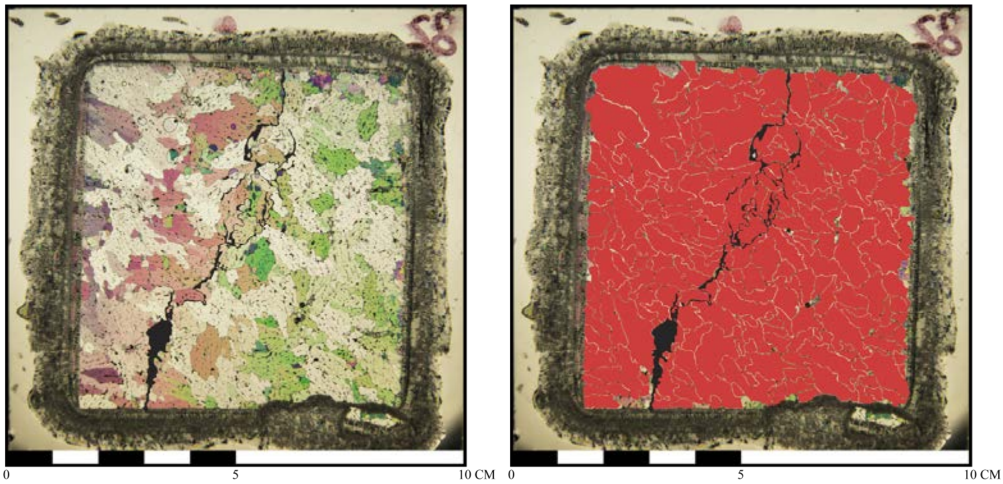


Illustration of needs/relevance for estimation of ice actions on structures.

DISCRETE NUMERICAL MODELLING

Discrete numerical modelling has been a key tool in modelling of global ice actions on floating structures at SAMCoT. This approach has been further developed by the NTNU spin-off company ArcISo in the Simulator for Arctic Marine Structures (SAMS). The simulator has been validated in terms of ice tank tests and ship transit in the marginal ice zone. Full scale data have been utilised to extract the 'measured ice load history' and compare with the numerical simulation results. Favourable comparisons were achieved both visually and quantitatively.



Crack propagation (from bottom to the top of the image) near crack tip zone, shown on the thin section S8 (depth z=-29cm) of ice sample in cross-polarized light (a) and with detected grains (b).

LOCAL ICE ACTIONS

For a structure-ice interaction process, a continuous record of force versus time can be converted to an ice pressure–area curve, or it can be used to find the specific energy of the mechanical destruction of ice (crushing specific energy), that is the energy required to crush a unit volume (or mass of ice). The highly empirical concept of the ice pressure–area relationship has been incorporated into design codes and practices, but use of the crushing specific energy is limited, although a theoretical and experimental basis exists for this value. In 2018, our focus was mainly on the specific energy concept and its application for ice impact problems. Researchers at SAMCoT have reviewed the development of the specific energy concept and argue that it is more convenient to use the specific energy for the description of certain ice-structure interaction scenarios, i.e., ice impact crushing with limited energy. Dr. Ekaterina Kim presented the results of this work during a plenary talk at IAHR2018 in Vladivostok.

As a part of this study, we have also conducted a survey among ice engineers and scientists from industry and academia. The purpose of this survey was to determine the current level of understanding and the current use of these two concepts. The number of completed surveys was low, however, our preliminary analysis of the response shows the following results.The specific energy concept is rarely used in engineering practice while the pressure area curves are considered to be more reliable and/or simple method for calculation of ice loads. The understanding of the global pressure area curves is generally better than that of the local pressure area curves and crushing specific energy.

As a part of the specific energy study, we have re-examined the experimental results obtained in the ice indentation tests. Interaction experiments with indentors of five different radii in a scale of 1:181 were analysed. Independent of the testing procedure (drop ball test / indentation tests), the mass-specific energy absorption capacity decreased with penetration and approached a horizontal asymptote for larger penetration depths. Although scattered, the mass-specific energy absorption capacity was weakly dependent on the indentor radius. For laboratory-grown ice, the tests indicate a specific energy of 13-14 kJ/kg. The in situ iceberg tests gave a value of approximately 3.0 kJ/kg. Application of different interaction theories (i.e., constant strength theory and strength theory with material softening (or the pressure-area model) to predict the average (quasi-static) force-displacement histories showed that the pressure-area model is capable of predicting force-displacement development, although one must be careful in setting the ice parameters, as it is easy to underestimate/overestimate the crushing specific energy of ice. Within the context of accidental limit state and energy absorption capacity of ice, it is better to directly use the force versus deformation curve rather than a pressure-area model.

Results of our three-year work in the Arctic Technology Committee of the International Ship and Offshore Structures Congress (ISSC) have been published in the report where several scientific results from SAMCoT have been highlighted and recommended for further use.

STRUCTURAL INTEGRITY OF SHIPS AND OFFSHORE STRUCTURES IMPACTED BY ICE

Floating glacial ice of various sizes pose great threats to the structural integrity of ships and offshore structures in the High North. In order to design reliable and cost-effective structures in the polar regions, it is essential to understand clearly the mechanical properties of ice and ice-structure interactions. Ice, as a nature material, has very complicated material behaviour under loading, which is often accompanied by complex fracture patterns. From structural design point of view we have focused on developing a 'design ice' model capturing major ice properties and energy absorption capabilities during crushing. He has studied further an existing hydrostatic-pressure dependent plasticity model of ice with associative flow rule. Because associative flow rule for geomaterials like soil, often leads to excessive dilatancy, we are exploring the influence of using associative and non-associative flow rule on the outcome. Besides, instead of calibrating to the ice-pressure area relationship, we calibrated the model to the resistance of ice crushing experiments, which is considered more accurate.

For the ice-structure interactions and structural responses under ice loading, both non-linear finite element methods (NLFEM) and simplified analytical methods are used. The shared energy scheme is used, where force-displacement curves are obtained assuming rigid ice-deformable structure and deformable ice-rigid structure collisions. Under the same force level, both ice and the structure should deform and dissipate energy. A simplified model was proposed for predicting the beam resistance of a single stiffened panels under lateral loading. The model was further extended to account for stiffened panels with several spans. The formulations were verified of reasonable accuracy by comparison with NLFEM simulations. Results showed that the boundary axial stiffness were crucial for stiffened panel response and a smaller axial stiffness will lead to a delayed development of axial forces and therefore larger deflections.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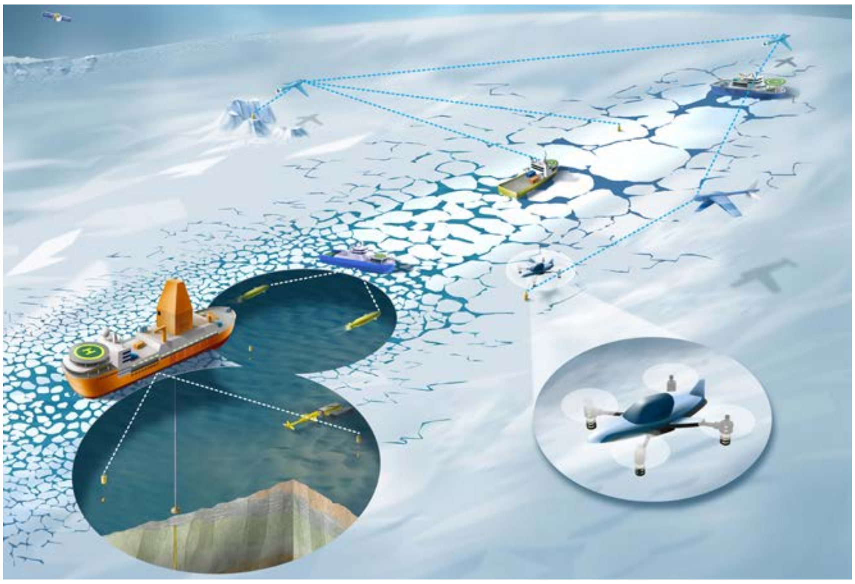
WP5 ICE MANAGEMENT AND DESIGN PHILOSOPHY

The purpose of WP5 has been to study design philosophies and methods ensuring safe operation of floating structures in presence of sea-ice and icebergs, by including ice management (IM) functions as part of the operational philosophy. The main research question has been how to mitigate hazardous situations by reducing or avoiding actions from any kind of floating ice at a specific location for planned operations by a protected unit. The goal has been to get to a philosophy that ensures that the Ultimate Limit State (ULS) and Accidental Limit State (ALS) requirements are fulfilled by Arctic offshore structures without being overly conservative. The means investigated in this WP to achieve this, have been the use of IM functions such as icebreakers, iceberg towing vessels, structure disconnection and reconnection capabilities, and a sophisticated ice surveillance system for online situational awareness of the ice environment. Specific subtopics have concerned:

- Decision making methodology and technology.
- Overall reliability estimation and online reliability monitoring of IM process.
- Iceberg detection, tracking, and forecasting – especially when embedded in sea-ice.
- Iceberg towing – especially when embedded in pack-ice.
- Prediction models for iceberg impact loads.
- Online monitoring and prediction of sea-ice loads.
- Sea-ice and iceberg drift models and monitoring systems, incl. detection of ice drift changes.
- Icebreaker deployment, coordination, and efficiency.
- Image acquisition and image processing for extracting ice parameters and statistical distributions from image datasets.
- Dynamic positioning (DP) and position mooring (PM) systems and operations in drifting sea-ice.

The WP has roughly defined 5 main innovation areas: 1) quantification of safety based on uncertain data, 2) ice risk and barrier management, 3) iceberg management, 4) ice surveillance, and 5) physical IM operations. The PhD resources of the WP5 have been 3 centre-financed PhD studies, while 3 additional PhD studies have been shared with the NTNU CoE on Autonomous Marine Operations and Systems (NTNU AMOS) on common and relevant topics. In addition, WP5 have partly involved 3 more researchers to work on innovative solutions proposed within the centre. The activities within quantification of safety and iceberg management were ended in 2016-2017, whereas the other activities have been continued to 2019.



Example Ice Management operation with a protected vessel, 3 icebreakers working upstream the ice drift, and several ice surveillance platforms.

UNCERTAINTY QUANTIFICATION IN VIEW OF LACK OF DATA

A particular challenge of IM-based Arctic offshore operations is the lack of experience and statistical data to learn and derive models from. Farzad Faridafshin studied this problem for the design of Arctic offshore structures, based on the research question: Explore alternative methods for uncertainty quantification in view of lack of data (particularly long-term metocean data).

In Farzad's work, three major alternatives are presented and explored for design of marine structures under uncertainty, these being stochastic, robust, and distributionally robust optimization frameworks. The first two methodologies relate to probabilistic (or reliability-based) and nonprobabilistic structural design methods respectively, which are well-established and understood in structural mechanics applications. The third alternative, not as much explored, specifically targets to immunize the design against the choice of (generally multivariate) probability distributions. Using this methodology, instead of requiring an inclusive joint probability density function (jpdf), more limited amount of prior information is extracted from a dataset. Such prior information can for example be the first or higher-order moments of a set of data, possibly in addition to some qualitative assumption regarding the shape and tail behavior of the underlying probability distribution. In this methodology, the incomplete knowledge of the distribution is invested in defining a distributional set, out of which the worst realization is sought for and forms the basis for design. In other words, the true distribution is unknown, but it is believed to belong to a set, out of which the worst one is chosen for design purposes. Farzad defended his thesis in June 2017.

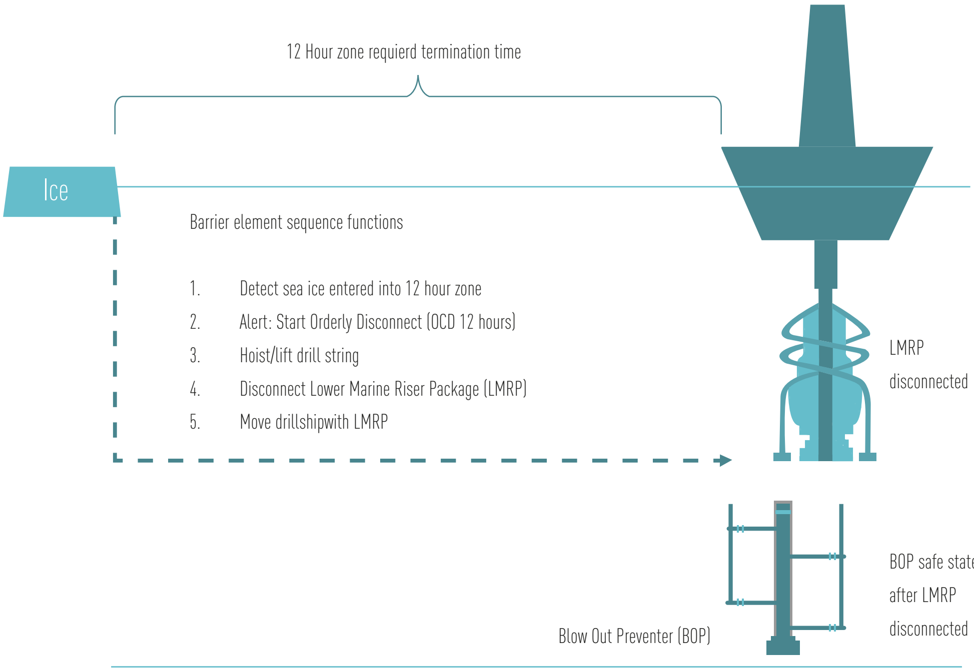


Illustration of one barrier in an event tree showing barrier element sequence functions.

ICE RISK AND BARRIER MANAGEMENT

Researcher Stian Ruud has studied ice risk and barrier management, with a focus on qualitative and quantitative barrier descriptions, using safe learning principles, and performance evaluation based on ALARP. Operators in Norwegian Arctic waters must comply with regulatory requirements as stated by the Petroleum Safety Authoritiy Norway (PSA) regarding risk management and with requirements stated in ISO 35104 "Arctic operations — Ice management" (published 2018).

PSA requires identification of defined hazards and accident conditions and in the IM context this could be collisions between ice floes and a drilling vessel connected to the seabed with a blowout preventer (BOP). PSA requires risk reduction by means of barriers. In the upper-right figure a barrier is indicated as a sequence of barrier element functions that should detect incoming ice and then start disconnection of the Lower Marine Riser Package (LMRP) from the BOP in order to bring the BOP, LMRP, and the drill ship into a safe disconnected state.

Cooperation between academic and industrial partners has enabled a conceptual IM approach based primarily on requirements of the national safety regulations. The method should be practically feasible for industrial applications and should also provide the basis for further industrial development and academic research. This work and its results were made possible thanks to contributions from SAMCoT partners: Equinor, DNV GL, Swedish Polar Research Secretariat, Arctic Marine Solutions (AMS) and NTNU, where AMS provided the report "Drilling in ice conditions, A case study for SAMCoT" in 2018.

ARCTIC ALLISION RISK MODELING

Martin Hassel performed his studies on risk analysis and modelling of allisions between vessels and offshore structures. Whereas the old models have typically used fault trees with much static information, his new model developed uses Bayesian belief networks.

ICEBERG MANAGEMENT

Renat Yulmetov defended his thesis in January 2017, where he studied modeling and simulation of icebergs drifting or being towed in broken ice. This included installing GPS trackers and measuring the drift of 9 icebergs and 10 ice floes off the coast North-East Greenland. In these data, the yawing motion of 4 icebergs were measured for the first time. A numerical model was developed, which also included towing of icebergs when embedded in sea ice. The numerical model of iceberg towing in broken ice was validated using data obtained in a model-scale towing experiment in the Hamburg Ship Model Basin.

ICE SURVEILLANCE

Within the area of ice surveillance, the Centre early started using camera imagery to document local ice conditions on various ship expeditions. A 360 degree omnidirectional camera system, a forward looking 180 degree camera system, downward looking ice thickness camera, and various cameras studying ice-vessel interaction and breaking mechanisms, were developed and used with success on the Arctic expeditions.

ICE IMAGE PROCESSING

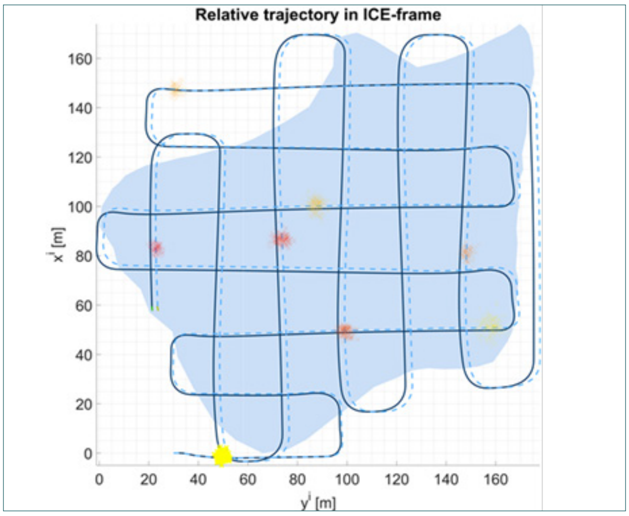
Having available large amount of ice image data, an early research activity was on image processing methods to extract relevant sea ice parameters such as ice concentration and floe size distributions. This was the topics of Qin Zhang, defending her PhD thesis in 2015, and later writing the Taylor & Francis monograph "Sea Ice Image Processing with Matlab".

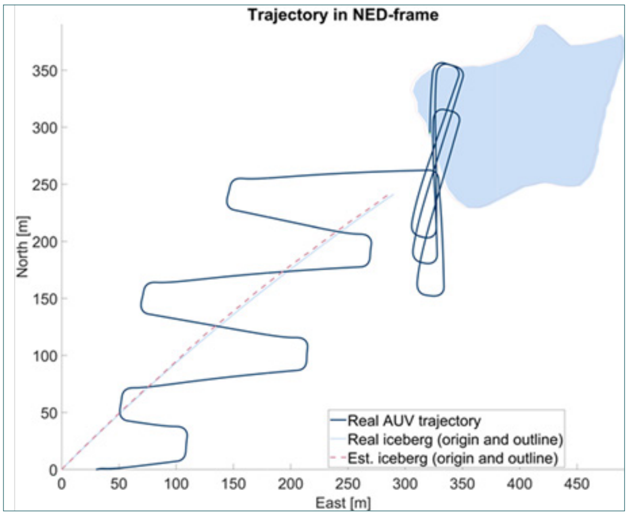
ONBOARD DECISION SUPPORT FROM ICE-INDUCED ACCELERATIONS

Hans-Martin Heyn, defending his thesis in 2019, was working on motion sensing on vessels operating in sea ice, particularly studying statistical modeling and change detection based on onboard measurements of ice-induced accelerations when moving the vessel through different forms of sea ice conditions.

ICEBERG MAPPING USING AUVS

Petter Norgren has been studying use of an AUVs and an upward-looking multibeam echosounder for mapping the underwater topography of sea ice and icebergs, and detection of ridge keels. Towards these goals, an important topic was to estimate the AUV position in an ice-fixed coordinate system using SLAM (Simultaneous Localization and Mapping). SLAM is method used to construct a map of an unknown environment and simultaneously to locate the vehicle in this map. Norgren developed an Arctic AUV simulator and an iceberg mapping estimator. He then tested this through simulations and with use of the experimental data collected with the HUGIN AUV in the Trondheim fjord, with his results published in a journal paper. The simulated trajectories shown below, using the Arctic AUV simulator, illustrates how the AUV performs in the moving ice-fixed coordinate frame. In September 2018, he defended his PhD thesis with the title "Autonomous underwater vehicles in Arctic marine operations: Arctic marine research and ice monitoring".





SLAM results from Arctic AUV simulator. Left subfigure shows trajectories in translating ice-relative coordinate frame; right subfigure shows trajectories in absolute coordinate frame.

ICE DRIFT MONITORING

Postdoc Øivind K. Kjerstad developed a method for online ice drift monitoring based on the ship's radar. The radar images are captured and sent as an image stream to the computer that performs image processing and detects common landmarks in each image. These landmarks are considered measurements in an extended Kalman filter to estimate the relative ship-ice drift velocity. The velocity of the ship also estimated and subtracted to output the absolute velocity of the ice cover.

PHYSICAL ICE MANAGEMENT OPERATIONS

Having implemented many activities on ice-risk based design and sea ice and iceberg surveillance and intelligence, the last defined innovation area has been on the actual physical IM operations. Øivind K. Kjerstad in his PhD thesis, defended in 2016, investigated mechanisms for robustifying the DP control system, with goal to develop an ice-capable DP system.

PhD candidate Jon Bjørnø has, on the other hand, been working on the icebreaker operations, where he has built a numerical model of an icebreaker operating in a realistically simulated sea ice environment. This is a high-fidelity simulation model of icebreaker actions and action effects, which Bjørnø is using as a platform for assessing icebreaker efficiency under different ice conditions, and he is formulating guidance and control strategies for deployment and operation of the icebreaking fleet.

Bjørnø has modeled the hulls of icebreakers Oden and Frej. In 2018, two new numerical vessel models of Oden and Frej were made, where a previous model of Oden was replaced with updated details. The process of making models for both vessels was similar, yet the process of making the Frej model was more challenging due to lack of digital drawings. SAMCoT`s partner, the Swedish Polar Research Secretariat, played then an important role by providing physical copies of the drawings of the icebreaker Frej.

To create the hull model Bjørnø used a 3D hull-modelling program to outline the vessels from the drawings and mark important points, frames and waterlines. Then, he exported these models to a 3D creation software for further processing. He divided the models into different objects based on the curvature of the hull, and created models consisting of convex surfaces only.

Finally, Bjørnø exported these models into .obj files, enabling import into the Simulator for Arctic Marine Structures (SAMS) for further analysis. The process resulted in high-resolution models for both Oden and Frej.

Models of icebreaker Oden

Model of icebreaker Frej.

WP6 COASTAL TECHNOLOGY

Coastal zone development in the Arctic is quite demanding. The construction of roads, harbours and other facilities in the Arctic faces several challenges, e.g. exposure to combined actions from waves, currents and sea ice, high coastal erosion rates, building on permafrost soils, remoteness and lack of local material suitable for construction purposes. Moreover, climate changes may result in a warmer Arctic with less sea-ice cover leading to higher wave forces on structures, more unstable permafrost soils and increasing rates of coastal erosion during the service lifetime of our structures.

The goal of WP6 from day one in SAMCoT has been to develop technology and guidelines needed by the industry for the design and development of environmentally friendly and sustainable coastal structures in the challenging Arctic areas. Over the years, WP6 provided new knowledge, analytical and numerical models to improve the prediction of: 1) Arctic coastal erosion; 2) the behaviour of frozen/thawing soils and 3) the influence of climate changes. Field- and laboratory work have been given special attention in WP6. Three sites both at Spitsbergen (Vestpynten) and northwest Russia (Varandey and Baydaratskaya Bay) were heavily instrumented and continually monitored during the past eight years. The observations and data from these sites enriched our understanding of the coastal erosion processes dominant in the Arctic and provided us with valuable data to validate our models. Looking back, we can proudly say that today the goal of WP6 has largely been achieved. The guidelines document entitled "Guidelines for development of coastal infrastructure in cold climate" and spectra of numerical models developed in the work package are examples of this achievement.

TECHNICAL GUIDELINES: DEVELOPMENT OF COASTAL INFRASTRUCTURE IN COLD CLIMATE

One of the main deliverables from WP6 is the guidelines for development of coastal infrastructure in cold climate. The design of coastal infrastructure in cold climate can include, entirely or partly, infrastructure traditionally classified as onshore, coastal, and offshore infrastructure. Boundaries for the coastal zone in cold climate are suggested by the guidelines. These boundaries were defined by the limits of distribution of distinct coastal processes and phenomena, permafrost, technological considerations, and other relevant considerations for infrastructure development.

In general, the design of coastal infrastructure in a given location shall (i) meet the technical requirements of the structure and (ii) be appropriate to withstand the environmental conditions.

Coastal processes are one of the key factors which influence the selection of the coastal infrastructure location and foundation design. They determine the stability of the different elements of the infrastructure, the land availability (erosion or aggradation), and eventually the overall existence of a given coastal land area where the infrastructure is to be located. Coastal processes are governed by geology and hydrometeorological factors and can be influenced by construction activities linked to infrastructure development. Because of the significance of coastal erosion for the design of sustainable coastal infrastructure in the Arctic, a considerable volume of the guidelines document was devoted to this phenomenon.


SINTEF

2019:00563- Unrestricted

Development of coastal infrastructure in cold climate

Summary Guideline

SFI SAMCoT report

Author(s)
Anatoly Sinitsyn
Ivan Depina, Yared Bekele, Stein Christensen, Dirk van Oosterhout

SINTEF Community
Rock and Soil Mechanics
2019-06-14

The structure of technical guidelines is organized in four parts:

Part I: Introduction and Generalities

Presents a description of the environmental conditions in the coastal zone of cold regions and the Arctic, processes governing evolution of the coastal zone, engineering methods for site investigations, Arctic constrains for data acquisition and planning, opportunities of remote sensing for data collection, approaches for multicriterial analysis in planning infrastructure, recommendations for development of sustainable infrastructure, and considerations due to climate change.

Part II: The Prospect stage

Presents approaches for selection of site locations and an overview of data needs at this stage.

Part III. The Design stage

Presents solutions and design considerations for structures in the coastal zone of cold regions and the Arctic and an overview of data needs at this stage.

Part IV. The Monitoring stage

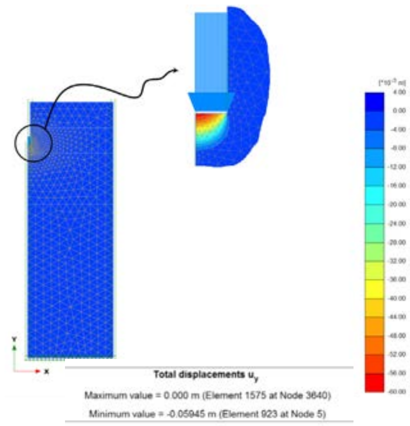
Presents considerations for monitoring of coastal infrastructure in cold regions and the Arctic.

NUMERICAL MODELLING OF FROZEN-SOIL BEHAVIOR: THERMO-HYDRO-MECHANICAL (THM) CONSTITUTIVE MODELS

Thermo-Hydro-Mechanical (THM) constitutive models for simulating the behaviour of frozen soils were developed in WP6. These are elastoplastic and an elasto-viscoplastic models to describe the mechanical behaviour as well as the behaviour due to variation of temperature. The proposed models are able to represent many of the fundamental features of the behaviour of frozen soils such as ice segregation phenomenon, strength weakening due to pressure melting and long-term creep deformation. These models are implemented in the commercial software package PLAXIS and are now readily available for geotechnical engineers.

ARCTIC COASTAL EROSION INVESTIGATIONS – FIELD INVESTIGATIONS AND THEORETICAL MOELLING

Since the start of SAMCoT, WP6 has been conducting field work at several sites at Spitsbergen (Vestpynten) and northwest Russia (Baydaratskaya Bay and Varandey) to collect full-scale data on Arctic coastal erosion. This includes monitoring the dominant erosion mechanisms, erosion rates, extent of coastal permafrost, ground thermal regimes and the ice and wave conditions at these locations. The field work provided valuable data that were used by several PhD students, MSc students and Postdoc in WP6 to validate theoretical models on coastal erosion, sediment transport, soil erodibility, coastal waves and local scours. It is no secret, that conducting continuous measurement and monitoring in the Arctic is a very challenging task, which we (in WP6) have succeeded in. The key to this success can certainly be attributed to the tight collaboration between NTNU, UNIS, SINTEF, State Oceanographic Institute (SOI) and Moscow State University (MSU).



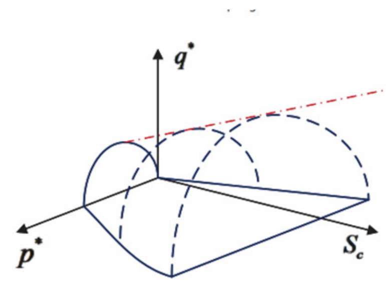


Figure WP6_1 Three-dimensional view of the yield surfaces in p*- q*- S space

LIST OF POST-DOCS, CANDIDATES FOR PHD AND MSC DEGREES DURING THE FULL PERIOD OF THE CENTRE

Post-doctoral researchers with financial support from the Centre budget

Name	M/F	Nationality	Years/period at the Centre	Scientific topic	Main contact
Anatoly Sinitsyn	M	Russian	2012-2013	Physical-mechanical properties and extent of coastal permafrost	S. Løset
Arttu Polojärvi	M	Finish	2013-2015	Discrete element modelling of ice rubble	J. Tuhkuri
Aleksey Shestov	M	Russian	2013-2018	Ice ridges properties	S. Løset
Seyed Ali Ghoreishian Amiri	M	Iranian	2014-2018	THM Engineering model (Elastic-Plastic-Creep)	G. Grimstad
Emilie Guegan	F	French	2015-2016	Erosion of permafrost affected coasts: rates, mechanisms and modelling	S. Nordal
Wenjun Lu	M	Chinese	2015-2017	Numerical modelling of ice-structure interaction	S. Løset
Andrei Tsarau	M	Belarusian	2015-2018	Floater-intact level ice interaction (processes in the waterline)	S. Løset
Mohammad Saud Afzal	M	Indian	2017-2017	Arctic Coastal Technology & Data Server	R. Lubbad
Hayo Hendrikse	M	Dutch	2017-2019	Ice-induced vibrations – numerical modelling	A Metrikine
Zhalong Yu	M	Chinese	2018-2019	Local ice loads and structural damage assessment	J. Amdahl

Post-doctoral researchers working on projects at the centre with financial support from other sources (In kind/RSO)

Name	M/F	Nationality	Source of funding	Years/period at the Centre	Scientific topic	Main contact
Øivind Kåre Kjerstad	M	Norwegian	NTNU	2015-2017	Arctic Marine Cybernetics	R. Skjetne
Nord Torodd Skjerve	M	Norwegian	NTNU	2015-2018	Ice-induced vibrations – analysis of measurements	K. Høyland
Sergey Kulyakhtin	M	Russian	NTNU	2016-2017	Constitutive modelling of ice rubble, FEM	K. Høyland
Ersegun Deniz Gedikli	M	Turkish	NTNU	2017-2019	Ice-induced vibrations of offshore structures	K. Høyland

PhD candidates who have completed with financial support from the Centre budget

Name	M/F	Nationality	Years/period at the Centre	Thesis title	Main supervisor
Lucie Strub-Klein	F	German	2011-2012	Field measurements and analysis of morthological, physical and mechanical properties of level ice and sea ice ridges	S. Løset
Aleksey Shestov	M	Russian	2011-2013	The Role of the Thermodynamic Consolidation of Ice Ridge Keels in the Seabed Gouging Process	A. Marchenko
Arttu Polojärvi	M	Finish	2011-2013	Sea ice ridge keel punch through experiments: model experiments and numerical mode-ling with discrete and combined finite-discrete element methods	J. Tuhkuri
Sergiy Sukhorukov	M	Russian	2011-2013	Ice-Ice and Ice-Steel Friction in Field and in Laboratory	S. Løset
Nord Torodd Skjerve	M	Norwegian	2011-2015	Force and response estimation on bottom-founded structures prone to ice-induced vibrations	K. Høyland
Oddgeir Dalane	M	Norwegian	2011-2014	Some Aspects of Conical Floaters Exposed to Ice Actions	S. Løset
Sergey Kulyakhtin	M	Russian	2011-2016	Unconsolidated ice rubble modelling with continuum approach	K. Høyland
Hayo Hendrikse	M	Dutch	2011-2017	Ice-Induces Vibrations of Vertically Sided Offshore Structures	A. Metrikine
Ole-Christian Ekeberg	M	Norwegian	2012-2015	Studies of ice ridge shape and geometry from upward looking sonar data	K. Høyland
Tsarau Andrei	M	Belarusian	2012-2015	Numerical Modelling of the Hydrodynamic Effects of Marine Operations in Broken Ice	S. Løset
Guegan Emilie	F	French	2012-2015	Erosion of permafrost affected coasts: rates, mechanisms and modelling	S. Nordal
Renat Yulmetov	M	Russian	2012-2017	Observations and Numerical Simulation of Icebergs in Broken Ice	A. Marchenko
Farzad Faridafshin	M	Iranian	2012-2017	Probabilistic, Non-probabilistic, and Distributionally Robust Approaches to Reliability Assessment: With a focus on the design of Arctic Offshore Structures	A. Næss
Chris Keijdener	M	Dutch	2013-2019	The effect of hydrodynamics on the interaction between floating structures and flexible ice floes. A study based on potential theory.	S. Løset
Nadeem Ahmad	M	Indian	2014-2018	High-Resolution CFD Modelling of Scour in the Marine Environment	Ø. Arntsen
Åse Ervik	F	Norwegian	2014-2019	Experimental and numerical studies related to failure of first-year ice ridges against fixed vertically sided structures	K. Høyland
Marnix van den Berg	M	Dutch	2014-2019	Discrete Numerical Modelling of the Interaction Between Broken Ice Fields and Structures	S. Løset

PhD candidates who have completed with other financial support, but associated with the Centre (In kind/RSO)

Name	M/F	Nationality	Source of funding	Years at the centre	Thesis title	Main supervisor
Daria Aleksutina	R	Russian	NTNU/MSU	2011-2016	Regularities in destruction of shores composed of fine-grained rocks depending on their composition, structure and properties - East coast of Baydaratskaya Bay	Marhenko, Rimma
Martin Storheim	M	Norwegian	NTNU	2011-2016	Structural response in ship-platform and ship-ice collisions	J. Amdahl
Ekaterina Kim	F	Russian	NTNU	2012-2014	Experimental and numerical studies related to coupled behavior of ice-mass and steel structures during accidental collisions	J. Amdahl
Bekele Yared Worku	M	Ethiopian	NTNU	2012-2016	Isogeometric Analysis of Coupled Problems in Porous Media	S. Nordal
Wenjun Lu	M	Chinese	NTNU	2013-2014	Floe Ice – Sloping Structure Interactions	S. Løset
Martin Hassel	M	Norwegian	NTNU	2013-2017	Risk Analysis and Modelling of Allisions between Passing Vessels and Offshore Installations	Ingrid B. Utne
Petter Norgren	M	Norwegian	NTNU	2013-2017	Autonomous underwater vehicles in Arctic marine operations	R. Skjetne
Qin Zhang	F	Chinese	NTNU	2014-2015	Image Processing for Ice Parameter Identification in Ice Management	R. Skjetne
Janne Ranta	M	Finish	NTNU/Aalto	2015-2018	Discrete element modeling of ice failure against an inclined structure. Statistical analyses of peak loads and the failure process	J. Tuhkuri
Hans-Martin Heyn	M	German	NTNU	2016-2019	Motion sensing on vessels operating in sea ice	R. Skjetne

PhD students with financial support from the Centre budget who still are in the process of finishing studies

Name	M/F	Nationality	Years at the Centre	Thesis topic	Main supervisor
Julie Malenfant-Lepage	F	Canadian	2016-2020	Experimental work on sediment Transport in Permafrost Area	R. Lubbad
Evgenii Salganik	M	Russian	2016-2020	Thermodynamic scaling of first year ice ridges	K. Høyland
Hongtao Li	M	Chinese	2017-2020	Modeling Wave-Ice interactions in the Marginal Ice Zone	R. Lubbad
Mark Shott	M	British	2016-2020	Consolidation of rafted sea ice and the associated risks to offshore structures in the arctic	K. Høyland
Ilija Samardzija	M	Chroatian	2017-2020	Risk, reliability and ice data in arctic marine environment – how to keep a sufficient safety level with little available data	K. Høyland
Runa Skarbø	F	Norweigan	2015-2020	Ice drift prediction and mitigation of impact from ice on marine operations	S. Løset
Jon Bjørnø	M	Norwegian	2016-2020	Motion sensing on vessels operating in sea ice. A local ice monitoring system for transit and stationkeeping operations under the influence of sea ice	R. Skjetne
Mohammad Akhsanul Islam	M	Bangladesh	2018-2020	Numerical Modeling of Short and Long term Erosion of Permafrost Coastal Bluffs	R. Lubbad

MSc candidates with thesis related to the Centre research agenda and an advisor from the Centre staff

Name	M/F	Nationality	MSc Year	Thesis title	Main thesis Advisor
Weizhi Ji	M	Chinese	2011	Finite Element Modelling of a Shear Box experiment on Ice Rubble	K. Høyland
Henning Helgøy	M	Norwegian	2012	Experimental Investigations of Freeze-Bonds between Saline Ice-Blocks	K. Høyland
Oda Skog Astrup	F	Norwegian	2012	Experimental Investigations and Analytical Analysis of Ice Rubble: Shear Box and Pile Testing	K. Høyland
Joar Aspenes Justad	M	Norwegian	2012	Experimental Investigations and Analytical Analysis of Ice Rubble: Shear Box and Pile Testing	K. Høyland
Maxim Yazarov	M	Russian	2012	One-Dimensional Viscoelastic Simulation of Ice Behaviour in relation to Dynamic Ice Action	K. Høyland
Ann Christin Hovland	F	Norwegian	2012	Ice Management - how to document reduced actions from managed ice on floating downward conical sloping structures	S. Løset
Anders Møllegaard	M	Norwegian	2012	Experimental study on freeze-bonds in laboratory made saline ice	K. Høyland
Jon Marius Aasheim	M	Norwegian	2012	Conceptual Design of Surface Buoy for Arctic Conditions	J. Amdahl
Mohammad Saud Afzal	M	Indian	2013	3D Numerical Modelling of Sediment Transport under Current and Waves	Ø- Arntsen
Åse Ervik	F	Norwegian	2013	Experimental and numerical investigation of cantilever beam tests in floating ice covers	K. Holte
Sverre Haug Lindseth	M	Norwegian	2013	Splitting as a Load Releasing Mechanism for a Floater in Ice	S. Løset
Sutrisno Sutrisno	M	Indonesian	2013	Numerical Analysis of Wave Transmission behind Floating Breakwaters	R. Lubbad
Mika Nikolai Sundland	M	Norwegian	2013	Guidance and control of iceberg towing operation in open water, with experimental testing	R. Skjetne
Rohit Rajesh Kulkarni	M	Indian	2013	Numerical Modelling of Coastal Erosion using MIKE21	R. Lubbad
Gunther Kassner	M	German	2013	The use of local soil as fill material for geotextile mattresses in arctic areas	A Watn
Henrik Emil Wold	M	Norwegian	2013	Thrust allocation for DP in ice	L. Imsland
Ida Mari Bueide	F	Norwegian	2014	Freeze-bond strength experiments, radially confined compression tests on saline and fresh water samples	K. Høyland
Nicolai Segaard Greaker	M	Norwegian	2014	Laboratory Measurements of Ice-concrete Abrasion with different Types of Ice Quality	K. Høyland
S. Kvadsheim	M	Norwegian	2014	Iceridge keel size distribution	K. Høyland
Cathrine Yvonne Pedersen	F	Norwegian	2014	Interfacial Study of Input Data in dynamic Ice-structure Interaction and Evaluation of Tactile Sensors Usability in Ice-related problems	K. Høyland
Andreas Orsten	M	Norwegian	2014	Automatic Reliability-based Control of Iceberg Towing in Open Waters	R. Skjetne

Name	M/F	Nationality	MSc Year	Thesis title	Main thesis Advisor
Thor Olav Myklebust	M	Norwegian	2014	Equipment and Production of Columnar Sea Ice Replica in NTNU Cold Lab	K. Høyland
N. Ganicheva	F	Russian	2014	Engineering structures in the coastal zone in the Arctic, the example of Vestpynten, Spitsbergen	A Marchenko
Carl Magnus Vindegg	N	Norwegian	2014	Stress measurements in landfast sea ice in Van Mijenfjorden in Svalbard	A. Bruland
Vegar Østhus	N	Norwegian	2014	Robust Adaptive Control of a Surface Vessel in Managed Ice Using Hybrid Position- and Force Control	L. Imsland
Ivar Aleksander Gjessing	N	Norwegian	2015	Control and simulation of a thruster-assisted moored offshore vessel in sea-ice	R. Skjetne
Zhengru Ren	M	Chinese	2015	Fault Tolerant Control of Thruster-Assisted Position Mooring System	R. Skjetne
Guro Larsen	F	Norwegian	2015	Ice Detection and Tracking Based on Satellite and Radar Images	R. Skjetne
Thor Billington	M	Norwegian	2015	Online shape estimation of icebergs at sea	R. Skjetne
Hege Lindbjør Nilsen	F	Norwegian	2015	Finite Element Simulations of Punch Tests on Ice Rubble with the Modified Cam Clay Model	K- Høyland
Syeda Wahida Rafiq	F	Indonesian	2015	Numerical Modelling of Sediment Transport in the Arctic	R. Lubbad
Sjur Moe Grevsgård	M	Norwegian	2015	Finite Element Simulations of Unconsolidated Keel Actions from First-Year ice ridges	K- Høyland
D. A. Ksenofontova	F	Russian	2015	Thermodynamic consolidation of broken ice and ice ridges	A Marchenko
Dimitrii Murashkin	M	Russian	2015	INFLUENCE OF BRINE MIGRATION ON TERMAL EXPANSION COEFFICIENT OF SEA ICE	A Marchenko
Jon Bjørno	M	Norwegian	2016	Thruster-assisted position mooring of C/S Inocean Cat I Drillship	R. Skjetne
Preben Frederich	M	Norwegian	2016	Constrained Optimal Thrust Allocation for C/S Inocean Cat I Drillship	R. Skjetne
Andrii Murdza	M	Russia	2016	Nvestigation of Sea Ice Strength Properties: Meso-Scale Tests and Numerical Modelling	A Marchenko
Ilija Samardžija	M	Chroatian	2016	Model Scale Test of Towing Operations in Managed Sea Ice	R. Lubbad
B.T. Borgensen	F	Norwegian	2016	Numerical Modelling of Arctic Coastal Hydrodynamics and Sediment Transport	R. Lubbad
Job Kramers	M	Dutch	2016	Global ice ridge ramming loads based on full scale data and specific energy approach	S. Løset
Hooman Rostami	M	Iranian	2017	Finite Element Analysis of Coupled Thermo-Hydro-Mechanical Processes in Fully Saturated, Partially Frozen Soils	G. Grimstad
Guttorm Udjus	M	Norwegian	2017	Force field identification and positioning control of an autonomous vessel using inertial measurement units	R. Skjetne
Silje Aarvik Johannessen	F	Norwegian	2017	Autonomous heading control in position mooring with thruster assist	R. Skjetne
Agnes Katharina Schneider	F	German	2017	Assessing Stability of Coastal Bluffs Due to Combined Actions of Waves and Changing Ambient Temperatures in the Arctic	R. Lubbad
Anne-Niekolai Heijkoop	F	Dutch	2017	Sea ice subjected to cyclic compression	A.V. Metrikine
Cody C. Owen	M	Dutch	2017	Ice-induced Vibrations of Vertically Sided Model Structures	H. Hendrikse
Maren Salte Kallelid	F	Norwegian	2018	A Study of the Strength and the Physical Properties of Glacier-ice Runways	K. Høyland
Fan Zhang	M	Chinese	2018	Rubble Macro-porosity of Level Ice Accumulation on Wide Sloping Offshore Structures	K. Høyland
Mohammad Akhsanul Islam	M	Bangladesh	2018	Erosion in the Arctic: A Thermoabrasion Model to Predict Shoreline Change After an Extreme Event	R. Lubbad
David Massey	M	USA	2018	Numerical Simulation of Ice-Rubble Mound Breakwater Interactions	R. Lubbad
Preben Jensen Hoel André Nilsson Rolandsen	M	Norwegian	2018	Digital Twin of Vessels in Arctic Environments - Extending a Simulation Environment to allow for External Control	D.G. Nguyen
Maren Elise Bengtson	F	Norwegian	2019	Assessment of Impact of Dredging on Sediment Transport at Borg Port	R. Lubbad
Nauman Raza	M	Pakistan	2019	Physical Model Study of Living Breakwaters; Stability and Ecological Analysis of Green-Grey Hybrid Structure Concept for Climate Change Adoption	R. Lubbad

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FIGURES 2019

SFI Annual Work Plan Total - Project Characteristics and Costs (All figures in 1000 NOK)

Item	Host NTNU	Stiftelsen SINTEF	UNIS	Equinor	Shell	DNV GL	TOTAL	Multiconsult	Kongsberg Maritime	SMSC	Exxonmobile URC	Neptune Energy Norge AS	AkerBP ASA	Lundin	Kværner	Norwegian Coastal Adm.	Swedish Polar Research Secretariat	DTU	UCL	HSVA	TUDelft	Aalto University	MSU	VTT	Total cost
WP1	550	231	32 549	129	172	98	343	201	70		4	45	32	7	161									635	35 226
WP2	13 614			111	189	116	321	1 492	70		4	45	32		73				321	87		3 103		611	20 188
WP3 & IVOS	28 088			161	239	124	455	1 729	193	168	4	45	32	7	163			250	731	4 577	6 083	3 908	208	2 168	49 332
WP4	32 127			161	239	155	455	181	418	168	4	45	32	7	163		2 103			149	2 791			458	39 655
WP5	44 467		7 748	6 417	199	310	454	202	275	163	4	45	32	7	212		2 143			15				57	59 749
WP6	13 722	26 495		156	171	137	743	412	70	6	4	45	32	7	163			793					2 367	57	45 378
EIAC				920	531	560	522	919	470	76	75	215	111	33	278										7 710
SAC	182			18			15															124			340
SFI Equipment	6 465	958	5 044	433															9	293		33	156		13 390
SFI Administration	19 982	3 529	4 883	683	280	367	466	327	229	31	99	675	154		102		10		50	136	158	143		155	32 458
Total budget	**159 198**	**31 212**	**47 224**	**9 189**	**2 020**	**1 868**	**3 774**	**5 462**	**1 795**	**612**	**197**	**1 160**	**455**	**66**	**1 314**		**4 256**	**1 043**	**1 111**	**5 257**	**9 032**	**7 311**	**2 731**	**4 140**	**300 425**

Summary Sheet for the main catgories of partners

Contributor	Cash	In-kind	Total
Host	0	55 505	55 505
Research partners	0	36 053	36 053
Companies	94 059	27 912	121 971
Public partners	2 640	4 256	6 896
RCN	80 000	0	80 000
Sum	**176 699**	**123 726**	**300 425**

SFI Annual Work Plan TOTAL - Funding (All figures in 1000 NOK)

ITEM	Host NTNU	Stiftelsen SINTEF	UNIS	Statoil	Shell	DNV GL	TOTAL	Multiconsult	Kongsberg Maritime	SMSC	Exxonmobile URC	Neptune Energy Norge AS	AkerBP	Lundin	Kværner	Norwegian Coastal Admin	Swedish Polar Research Secretariat	DTU	UCL	HSVA	TUDelft	Aalto University	MSU	VTT	RCN Grant	Total cost
WP1	35		8 226	1 587	1 222	1 478	1 849	1 109	420	138	534	1 134	1 049	897	745	151								635	12 793	34 002
WP2	4 375			1 012	1 120	1 031	1 250	1 919	301	138	387	987	852	444	457	151			205	87		1 626		887	8 610	25 837
WP3 & IVOS	13 565			1 534	1 380	1 567	1 970	2 356	666	305	534	1 224	1 249	897	835	151		250	371	1 612	2 072	1 905	123	1 467	11 703	47 737
WP4	15 058			1 508	1 290	1 508	1 880	1 090	891	305	534	1 134	1 249	897	745	151	2 103			149	7			58	11 739	42 298
WP5	7 357			40 271	1 222	1 493	1 880	1 241	749	301	534	1 134	1 249	897	745	151	2 143			15				57	11 374	72 812
WP6	2 964	5 746		1 500	1 222	1 491	2 000	1 191	543	143	534	1 134	1 247	897	746	1 884		793					2 073	57	12 996	39 159
EIAC				8 47	515	607	444	871	435	76	52	245	343	138	321											4 895
SAC																					38	46			96	180
SFI Equipment		377		858																293			133			1 661
SFI Administration	12 152	3 024	3 212	507	158	197	298	187	113	31	32	560	110		52		10		50	136	74	97		155	10 691	31 845
Total budget	**55 505**	**9 147**	**11 439**	**49 625**	**8 129**	**9 372**	**11 571**	**9 963**	**4 118**	**1 437**	**3 142**	**7 551**	**7 348**	**5 069**	**4 648**	**2 640**	**4 256**	**1 043**	**626**	**2 292**	**2 191**	**3 674**	**2 329**	**3 315**	**80 000**	**300 425**

Distribution of resoures

Type of activity	NOK million
WP1	35 226
WP2	20 188
WP3 & IVOS	49 332
WP4	39 655
WP5	59 749
WP6	45 378
EIAC	4 710
SAC	340
SFI Equipment	13 390
SFI Administration	32 458
Total budget	**300 425**