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Anatoly O. Sinitsyn • Ivan Depina • Yared Bekele
Stein Christensen • Dirk van Oosterhout

Development of coastal infrastructure in cold climate Summary Guideline

SFI SAMCoT REPORT

SINTEF Research

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Front page picture: coastal bluff at Vestpynten (Svalbard) in autumn, winter, spring, and summer (2014–2015). Pictures are taken by the time lapse camera installed by PhD student (at the time) Emilie Guegan to reveal processes governing coastal erosion at the site.

SINTEF Academic Press
P.O.Box 124 Blindern
N-0314 OSLO
Phone: +47 400 05 100
www.sintef.no/community
www.sintefbok.no

Foreword

This report is a Summary Guideline for development of coastal infrastructure in cold climate and is prepared within the SFI Sustainable Arctic Marine and Coastal Technology (SAMCoT).

The Summary Guideline follows the structure of a more comprehensive Technical Guideline established within the SFI, both aiming to give guidelines needed by the industry for the design of environmentally friendly and sustainable coastal structures and technology in cold regions. Recommendations are provided where appropriate and possible following the Prospect stage, the Design stage, and the Monitoring stage.

Trondheim, 24.06.2020

Lisbeth-Ingrid Alnæs
Research Manager
SINTEF Community

Anatoly O. Sinitsyn
Project Leader
SINTEF Community

SAMCoT

This document has been prepared within the Center for Research-based Innovation (CRI - SFI SAMCoT in the following) *Sustainable Arctic Marine and Coastal Technology*, 2011–2019 (SAMCoT, https://www.ntnu.edu/samcot). SFI SAMCoT was established by the Research Council of Norway to meet the needs related to the increase in activities in waters such as the Eurasian Arctic, East Greenland and the Chukchi Sea.

SFI SAMCoT has been a leading national and international centre for the development of robust technology needed by the industry for sustainable exploration and exploitation of the valuable and vulnerable Arctic region. SFI SAMCoT met the challenges due to ice, permafrost and changing climate for the benefit of the energy sector and society.

SFI SAMCoT has been hosted and lead by NTNU, and managed by NTNU, SINTEF and UNIS. The SFI has included Industry Partners, Research Partners, International Research Parties, and Public Partners.

The Industry Partners defined six sets of main challenge and cooperation fields (Work Packages – WPs) for which long and medium term strategically important research was required to help reduce risks when deploying and using technologies for oil and gas exploration and exploitation, and for engineering activities in the coastal zone. WPs at SFI SAMCoT were: WP1 Collection & analysis of field data and properties; WP2 Material Modelling; WP3 Fixed Structures in Ice; WP4 Floating Structures in Ice; WP5 Ice Management and Design Philosophy; WP6 Coastal Technology.

This document is prepared as part of the deliverables for WP6 Coastal Technology. The present Summary Guideline is prepared to answer the overall objective of WP6, which is to develop guidelines needed by the industry for the design of environmentally friendly and sustainable coastal structures and technology.

Acknowledgements

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We are also thankful to Dr. Emilie Guegan for her PhD thesis whose chapter on coastal modelling served as basis for considerations on coastal modelling of permafrost-affected coastlines. We thank Martin Carpentier who elaborated basis for Multi-criteria analysis during his internship at SINTEF in summer 2017.

Disclaimer

The intention of the Summary Guideline and the Technical Guideline is to assist in the design of coastal infrastructure in cold regions. The guideline is nevertheless not meant to be a rigid description of recommendations.

Authors and their organizations do not hold any responsibility due to any losses associated with the use of the present document.

Contents

Part I. Introduction

Scope of the SAMCoT Guideline

The design of coastal infrastructure in cold climate can include, entirely or partly, infrastructure traditionally classified as onshore, coastal, and offshore infrastructure. Infrastructure located within the limits of the coastal zone is classified as coastal in the present document. Boundaries for the coastal zone in cold climate in across shore direction are suggested and presented in Part I, Ch. "Coastal terminology of the SAMCoT Guideline". 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.

Designing coastal infrastructure in a given location shall (i) meet 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 coastal infrastructure location and foundation design. Coastal processes influence the selection of infrastructure location, stability of the different elements of infrastructure, direction of evaluation of certain coastal stretch (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. Distinct significance of coastal erosion in design of sustainable coastal infrastructure in the Arctic results in a considerable volume of the present document devoted to this phenomenon.

The present Summary Guideline follows the same structure as the Technical Guideline (TG)[1], which is organized in four parts:

Part I. Introduction and Generalities

Presents a description of 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.

Geographical boundaries for the SAMCoT Guideline

The coasts of cold regions are geographic areas of presumed development of coastal structures and technologies. A significant part of such coasts is present in the zone of the Arctic Ocean. The TG does not answer to particularities of infrastructure development related to coastlines presenting shelf ice (glacier ice) and coasts with perennial landfast ice, and therefore these are excluded from considerations. Hereafter cold regions are defined from an engineering point of view. The presence of at least one of the following factors is enough to relate a certain location to cold regions:

1. Cold air temperatures
2. Seasonal frost penetration
3. Seasonal or perennial sea-ice cover and/or ice cover on rivers
4. Permafrost, including ground ice

Superimposing factors 1 to 4 provides geographical boundaries for cold regions. Median values based on long-term observations (of at least 30 years) may be used for defining the above-mentioned geographic boundaries. Possible future boundaries of the SAMCoT Guideline may be defined based on data obtained from climate

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[1] Technical Guideline. Guidelines for development of coastal infrastructure in cold climate. Sinitsyn, A., Depina, I., Bekele, Y., Christensen, S., van Oosterhout, D. SINTEF Report 2019:00474 (Restricted), ISBN 978-82-14-06325-7, 508 pp, 2019

projections. The TG provides an overview of distribution of cold air temperatures, seasonal frost penetration, sea ice and permafrost at global scale. A map presenting boundaries of cold regions following the consideration above is presented in Figure 1. On this map, factors (1)–(2) is presented by the 40th parallel and the limit of substantial frost penetration (from [1]); factor (3) – by median sea ice extent in the Northern Hemisphere for 1979–2000 (from [2]); factor (4) – by the permafrost distribution in the Northern Hemisphere ([3, 4], [5]); the AMAP area ([6]) is presented for the comparison.

Figure 1. Geographic boundaries defining extent of the Guideline. Sources: limit of substantial frost penetration – [1]; median sea ice extent in the Northern Hemisphere for 1979–2000 – [2]; Permafrost map on Northern Hemisphere – GRID-Arendal/Nunataryuk [5]; AMAP area – [6].

The Coasts of Arctic Ocean northward of the Polar or Arctic Circle are called *high-latitude coasts* and obviously located "inside" or present the "core" of cold regions. Many of these coasts are characterized by the presence of all four conditions 1 to 4. The cumulative effect of factors 2, 3 and 4 may lead in some cases to very high rates of coastal erosion in the Arctic regions. Specific challenges for infrastructure in coastal zone due to the presence of factors 1 to 4 are summarized in Table 1. These challenges are different and are additional to the ones possible to encounter in the temperate and tropical zones.

Table 1
Determining factors of the cold regions and specific challenges related to coastal infrastructure

Factors	Specific challenges
1. Cold air temperatures	• Technological difficulties to processes as wet processes (concreting works), freezing of water in drainage systems, etc. • Specific phenomena, as icing and accretion of ice on elements of coastal structures due to tidal change. These phenomena may lead to specific types of loads on structures. • Snow, this phenomenon causes specific types of loads, influences ground thermal regime and hydrology.
2. Seasonal frost penetration	• Regions within the limits of substantial frost penetration in temperate climate. Seasonal frost penetration into the ground in these regions may lead to challenges associated with frost heave and thaw settlement.
3. Seasonal or perennial sea-ice cover, ice cover on rivers	• Ice imposes loads and actions on structures. • Ice acts as an agent, responsible for shaping different morphological elements of coastal zone: o Land fast sea ice provides protection role of the shore. o Sea ice may provide sediment transport by capturing suspended sediment during freezing and subsequent transportation by drift ice. o Ice ridges and icebergs may deform the seabed, and hence lead to imbalance of idealized shoreface slope. o Level sea ice provides background for strudel scours. o Chunks of sea ice may do geomorphological work of shoreface in storm conditions.
4. Presence of permafrost	• Engineering design in permafrost zone is (to large degree) based on the behavior of frozen ground. Engineering design requires understanding subsurface temperatures, active layer, permafrost, and their development within life circle of a structure. • Ground ice – specific requirements to geotechnical design. • Perennial frost heave. • Lower degree of knowledge in geotechnical engineering for permafrost conditions (when compared to temperate climate), in particular: o Lesser experience in infrastructure development. o Sparse data on ground properties. • The number of available models for description of "stress-strain" behaviors is considerably lesser than for the ground in unfrozen state.

Coastal processes and phenomena

Current philosophy of coastal research

The dominant paradigm for describing coastal systems is a morphodynamic approach, [7]. According to this paradigm, coastal systems are comprised by three linked elements: morphology, processes, and sediment transport. Environmental factors (referred as "boundary conditions") include (i) solid boundary (geology and sediments), (ii) climate and external forces (wind, waves, storms, tides and tsunamis), and (iii) sea level. Human activities (as coastal structures, etc.) can be an additional driving force in controlling coastal dynamics and should be considered. In addition, alternation of the boundary conditions (sea-level rise and changes in wave conditions) may occur due to climate change. In permafrost-affected coastlines, the ground ice is a geological factor, and the sea ice is a factor which may be responsible for sediment transport and for external forcing.

Factors influencing coastal geology

Factors influencing coastal geology are outlined in details in the TG based on the Coastal Engineering Manual (*CEM* [8]). These factors include: underlying geology and geomorphology, high-frequency dynamic processes (waves, tides), sea-level changes (short- and long-term sea-level changes), geologic implications of sea level change (sediment type, sediment supply, coastal platform, and regional tectonics), meteorology, biological factors, cultural (man-made) influences on coastal geology.

The *CEM* focuses on geology of the coastal zone. The Arctic coasts are included in the *CEM*, which indicates that coastal dynamics or behaviour of such coasts in general comply with dependencies governing coastal dynamics in temperate climate. Mechanisms of distinct Arctic coastal processes are, however, almost not described in the *CEM*.

Artic coasts exhibit in general similarities to coasts in temperate climate [9], i.e. the shape of shoreface profiles of unconsolidated coasts in the Arctic seas (for example on Laptev, Beaufort, and Chukchi Seas) is similar to seas in temperate climate [9, 10]. The latter studies outline that sea ice plays an important role in sediment transport resulting in significant changes of the shoreface relief. Another effect consists in the protective role of sea ice for the shores. Large ice and silt content result in average rates of coastal retreat which are higher than in the temperate environments [9].

Classification schemes for Arctic coasts

Classification schemes for coastal environments are the "tools" required for various practical applications. The Arctic Coastal Dynamics (ACD) classification [11] and the morphogenetic classification for the Arctic coastal zone [12] (based on the ACD classification) are the main classification available for the Arctic coasts.

Geomorphology and general behaviour of Arctic coasts

All major types of geomorphological features are present on Arctic coastlines, including sandy and gravel beaches, barrier islands, spits, deltas, salt marshes, low-angle tundra slopes, rocky cliffs and lagoons.

Sandy and gravel beaches. Erosional and depositional processes are typical for these features. Seasonal changes of shoreline position on clastic coastal areas occur under influence of cross-shore sediment transport. Long-shore sediment transport is one of the main factors determining whether shore will erode, accrete or remain stable in a long-term perspective. Another important process in the littoral zone is the wind-blown sediment transport, which can lead to removal and redistribution of sand. The wind-blown sediment transport is a driving factor in creation and development of dunes. In cold and Arctic regions, long-shore and cross-shore sediment transport is normally limited to the period of open water. Landfast ice, and drift ice (to some degree) define conditions for existence of these types of sediment transport via control of conditions for development of waves. Effect of some other sea ice-driven processes are also possible in these geomorphological features.

Barrier islands. Depositional features may be prone to erosion processes. The typical geomorphological form of the shore zone of barrier islands is sandy beaches, the section above outlines the processes relevant to this geomorphological feature. However, one must bear in mind, that the nearshore of barrier islands can be present by the cohesive shore, and this particularity will have a primary effect of the shore dynamics. Processes defining shore dynamics of a cohesive shore are in principle different from the ones mentioned above for sandy (clastic) shores. Examples of studies of dynamics of barrier islands in cold climate are presented for instance in [13] (the southeast Chukchi Sea), and [14] (the Varandey region, Barents Sea).

Spits. Depositional features usually following eroding coastal segments. However, spits may be prone to erosion.

Deltas. Depositional landform, which morphology is dependent on several factors controlling deposition. These factors are riverine, wave, and tidal processes. Other factors are landscape position and sediment characteristics provided by river [15-17]. Dynamics of Arctic deltas is discussed in [18]pp. 29-32]. Case study of coastal dynamics of deltaic areas in Artic is e.g. the mouth of Mackenzie River which is presented in [19]. Spatial extent of Arctic river deltas is presented in [20].

Salt marshes. Depositional landform.

Low-angle tundra slopes. Cliffs are one of the main backshore landforms. The presence of till or glacial cliff signalise that the shore is cohesive. The morphology of coastal cliffs may range from vegetated stable slopes, to eroding cliffs without vegetation cover, and to almost vertical wave-washed cliffs. The main processes acting on cliffs are: gullying (or thermal erosion) and nivation; basal wave-cut notch development (or development of thermal abrasive niche), this process is typical for cliffs composed from ice-rich sediment, possibly including ice wedges; thermal denudation, which is the process shaping features known as retrogressive thaw failures (RTF)/retrogressive thaw slumps/thermo-cirques/thermo-terraces, shallow sloughing (active layer detachments/slides).

Rocky cliffs. Rocky are usually considered to be stable for any given period of time when related to infrastructure. This feature may, however, be prone to coastal erosion if composed from soft sedimentary rock; the process of frost weathering may also affect rocky cliffs.

Lagoons. In Arctic environment, lagoons may occur at breached places due to coastal erosion lakes. Eroding shorelines may lead to breaching of nearby lakes. Lakes either drain or inundate after breaching, the latter depends on the lake bottom elevation relative to sea level [21]. In case if inundation, a breached lake may transform into a lagoon.

Two categories of coasts are present in the Arctic categories [22]: coastal landscapes in low-relief areas and coastal landscapes in high-relief areas. Most of the sedimentary landforms of Arctic coasts are associated with coastal plains (low-relief areas). The present document is focused on low-relief areas. High-relief areas (as along fjords) host other types of morphologies (as rocky cliffs) [22].

Unconsolidated coasts occupy 65% of Arctic coasts, the other 35% are presented by consolidated coasts [11]. Consolidated coasts (or "lithified" in terms of [11]) consist of rock material, which is firm and coherent. Such coasts are usually considered to be stable for any given period when related to infrastructure. Hence, further discussion on characteristics defining susceptibility to erosion and weathering of such coasts (mineral composition and degree of consolidation [8]) is given minor consideration in the present document.

Unconsolidated coasts (or "unlithified" in terms applied in [8, 11]) in the Arctic, similar to coasts in temperate climate, are presented by two types: loose clastic ("sandy") coasts and cohesive shores. It is worth repeating that "depositional and erosional processes dominate unconsolidated coasts" [8].

Loose clastic ("sandy") shores are characterised by erosion (or deposition). Erosion is potentially a reversible process. Based on the picture of prevailing coastal dynamics, one can outline two types of clastic shores: accumulative (clastic coast where deposition of the shoreline is observed) and abrasive (clastic coasts where erosion of the shoreline is observed).

The behaviour of clastic shores in the Arctic are, in general, similar to those ones in temperate climate. Hence, their dynamics is described by corresponding approaches. Arctic "particularities" of such coasts consist in a protective role of the sea ice cover against waves action, possible sediment entrapment and transport by sea ice, particularities of sediment transport under sea ice, local phenomena as strudel scour, and actions on sea bottom from ice features like ice ridges and icebergs. The latter phenomena shall be taken into account when their impact is considerable in a specific situation.

Cohesive shores in the Arctic are, similarly to temperate climate, presented by consolidated and unconsolidated cohesive (mud shore) shores. "Erosion on a consolidated cohesive shore is irreversible", and unconsolidated mud shores "are generally the result of more recent deposition of cohesive sediment" ([7], Part III, Chapter V). Unconsolidated cohesive shores occur in protected waters and are not discussed further herein.

Cohesive consolidated coasts in the Arctic are normally characterized by the presence of excess ice. The presence of excess ice leads to specific Arctic coastal processes, which are usually termed as "thermal abrasion" and "thermal denudation". Thermal abrasion normally (but not always, which is the case for coasts with extremely high ice content) is considered the primary (or driving) process, and thermal denudation is considered the secondary process[2]. Such subordination of the processes is in line with processes of cohesive shores in temperate climate. Two types of cohesive shores (with excess ice) in Arctic conditions may be distinguished as thermal abrasive and thermal denudative.

An overwhelming part of Arctic coasts is erosional, recession rates have high temporal (related to storminess, thermal conditions, and sea-ice conditions in the coastal zone [23], which in turn are driven by internal and decadal-scale fluctuations in atmospheric and hydrodynamic forcing) and spatial variability which is "largely

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[2] "Thermal abrasion leads to retreat of the coasts", and "thermal denudation wears down the cliffs" [46].

a function of geological, cryological (ground ice and permafrost) and geomorphological (including exposure) conditions controlling erodibility of coastal materials and the littoral sediment supply" [19]. The average shoreline erosion rate in the Arctic is 0.5 m/yr [11]. A snap-shot of Arctic coastal dynamics is presented at [24]. A regional analysis of processes in the Arctic Coastal Zone is presented in [25]. Other shores (in the contrast to erosional coasts) demonstrate long-term stability due to balanced sediment supply and little relative sea level rise.

Geomorphology and processes in the zones the adjacent the coastal zone

Chapters of the TG "Geomorphological features of the Shoreface, Continental shelf, Continental slope, and Continental Rise, and Abyssal plain" and "Onshore geomorphological features" are excluded from the Summary Guideline due to their limited relevance to the coastal zone. Knowledge on geomorphological features in these zones, is however, of primary importance for planning of routing infrastructure, which is crossing these zones (for instance a pipeline or a port project). Arctic-specific geomorphological features in these zones are outlined below.

Onshore Arctic-specific geomorphological features include various thermokarst features; pingo; landscape forms corresponding to Arctic specific slope processes: retrogressive thaw slumps, other slope processes; the Gas Emission Craters (GEC, as the "Yamal" craters). Morphological conditions of a GEC on Yamal are presented for instance in [26], dynamics (geomorphodynamics) of GEC – [27], field assessment of risk zones related to GEC – [28].

In Arctic sea, specific submarine glacier landforms can be found, information about these features is presented for instance in [29]. Specific geomorphological features (including submarine glacier landforms) of Arctic seas are: iceberg ploughmarks; ice ridge ploughmarks (these phenomena for instance described in [30-34]); drumlin (mound of glacial debris); glacial lineation; glacial erosional escarpment; glaciotectonic hole-hill pair; grounded iceberg depression; sub-sea "pingo-like features"; craters possibly associated with gas hydrates; strudel scours.

Ground temperatures and Permafrost

The ground conditions of permafrost-affected coastlines have a transition from the land to the ocean. Conceptual scheme of ground thermal conditions in permafrost-affected coastline are presented in [35] and reproduced in Figure 3. Five distinct regions can be distinguished in the transition of permafrost from subaerial to sub-sea conditions. Each region represents different thermal and chemical surface boundary conditions [35].

A typical temperature permafrost profile of perennially frozen soil in terrestrial environment includes: (i) the active layer, (ii) permafrost layer, (iii) depth of zero annual amplitude, and (iv) geothermal gradient. The reader may find more details, for instance in [36].

Sub-sea permafrost "is defined as permafrost occurring beneath the sea bed" [35]. Sub-sea permafrost is in most cases the permafrost, which was created in subaerial conditions, and at later stage inundated by the sea. Terrestrial landscapes are transformed into marine environments by coastal erosion and flooding [37]. Sub-sea permafrost is normally covered by a layer of unfrozen soil (known as "talik"), which maybe is nevertheless at negative temperature, and hence is classified as permafrost. The following types of sub-sea permafrost exist [61]: ice-bearing, ice-bonded and non-ice-bearing (thawed). Sub-sea permafrost is relict, warm and generally degrading [35]. Sub-sea permafrost becomes nearly isothermal over timescales up to a few Millennia after inundation [35]. The thermal regime of the nearshore sediments is controlled by the erosional and accumulative dynamics [21]. On one hand, warming of permafrost and deepening of the permafrost table can be observed at actively eroding shorelines [35, 38]. On the other hand, aggradation of permafrost may take place in areas of sediment deposition, where water depths permit formation of bottom-fast sea ice. Examples of warming of recently inundated (due coastal erosion) cold sub-sea permafrost are presented for instance in [35, 38]. More recently inundated permafrost is colder than the ones inundated before [35]; [21]. Overduin et al. [39] concluded that for near-shore permafrost in Siberia "permafrost temperature changes rapidly following inundation, thawing of permafrost is longer (m to mm per year)".

An engineer must be aware of several specific geo-cryological phenomena confined to sub-sea permafrost. Possibilities for locating structures in the areas with presence of such phenomena are limited or completely absent. In any case, these phenomena must be taken into considerations in design. These phenomena are: sub-sea pingos of different origin; taliks (open and closed), see details, for instance in [40]; deposits of gas hydrates.

Local anthropogenic activities

Local anthropogenic activities may have impact on coastal morphodynamics and infrastructures in coastal zones. The following local anthropogenic activities may take place in coastal zones (but are not limited to):

Coast – disturbance of vegetation; disturbance of drainage; withdrawal of subsurface fluids and gas mining; sediment loading; withdrawal or of sediments from the dune belt; interruption of sediment supply and transport; interruption of water level variations.

Shore and shoreface – withdrawal of sediments (dredging, in the sea and in river mouths), beach nourishment; removal of subsurface resources; engineering structures (landfalls, pipelines), river basin regulation works (constructions of dams); changes of the shoreline geometry (construction of new basins) and properties (installation of sheet pile walls, etc.).

Offshore – removal (offshore) of subsurface recourses; engineering structures (gravity platforms, sea floor installations).

Processes in coastal zone and in the adjacent zones

Global littoral processes (subaqueous processes) A discussion on the complex interactions between mechanisms that operated at different temporal and spatial scales to shape a coastal profile is presented, for instance, in [8, 41]. The following two processes were not considered in the TG: deltaic processes and processes of coastal inlets. Processes offshore are mainly accumulative (processes of suspended load precipitation or normal sedimentation), "these processes are controlled by currents, circular eddies, and extreme storms" [12].

Processes on **consolidated coasts** are, for instance, presented in [42, 43]; processes on **clastic sediment beaches and cohesive shores**, for instance, presented in [8].

Global terrestrial processes. These processes can be divided between gravity and atmospheric-induced processes. Because beaches typically slope seaward across the entire profile, gravity engenders typical downward movement of soil particles in the offshore direction [41]. Atmospheric and climatic processes inferring with the shaping of coastal zones include precipitation (type, intensity, and duration), solar energy, evapotranspiration, temperature (range, magnitude and frequency) and wind (intensity and direction). These climatic factors affect both the onshore and offshore parts of the system.

The presence or absence of vegetation affects both the sedimentation rate and the erosion. Animals’ activities on all levels (bioturbation activities, bird nests on coastal cliffs and pasturage activity) accelerate erosion processes through abrasion.

Main types of subaerial processes are:

1. Wind-blown sediment transport.
2. Gravity processes. These processes can be greatly intensified by precipitation. Typical types of mass movements of typical gravitational failure events are presented, for instance, in [44].
3. Fluvial processes, processes caused by action of running water on the ground surface ("surface wash"), i.e. surface erosion.
4. Weathering of sediment due to wind action.

Arctic-specific coastal processes. Arctic-specific coastal processes include: thermal abrasion; thermal denudation as primary process; processes related to the sea ice – protective role of sea ice, processes of sediment transport by sea ice from shallows areas, ice gouging, ice wallow, scours at grounded ice ridges, ice bulldozing, ice pile-up and ride-up (ice encroachment), ice-foot processes; marine phenomenon due to riverine processes – strudel scour; specific thermal processes – aggradation of newly formed permafrost on tidal flats, seasonal freezing of the shore; other specific processes – wave action of calving glaciers or icebergs on the coasts.

Thermal abrasion. "Thermal abrasion is the process of erosion of coasts made up of permafrost under the combined action of the mechanical and thermal energy of the sea" [45]. The process represents block failure erosion initiated by the development of a thermoerosion niche [46]. The niche is generated by breaking waves and storm surge on the lower bluff (Figure 2). The development of a thermoerosional niche is the key process of thermal abrasion. Analytical modelling by [47] showed that the niche may develop both in the presence or absence of an ice wedge, but the permafrost soil must be ice bonded. Field observations show that thermoerosional niches and ice wedges are key factors contributing to the block failure mechanisms. Probable block failure mechanisms are sliding and toppling. Potential block failure modes are considered in [47], and are dependent on cliff geometry, rheology of cliff soil, ice wedge presence and location. The temporal character of the niche development depends on local water depth, sea water temperature, and wave conditions. Niche development is a cyclic process. After collapsing, blocks are eroded by waves. During this time, they protect the coastal bluff from wave action. A new niche begins to form when the collapsed block is reworked (eroded) by the sea [46] (Figure 2).

The main factors of climate change which need to be taken into account in assessment of long-term rates of thermal abrasion are: (i) changes of rheological behavior (via air temperatures, and hence changes of permafrost temperatures), and (ii) parameters defining temporal rates of the thermoerosional niche development (sea water temperature, storm activity and sea-level rise) [47]. Both types of situations, with high erosion rates over several years and deceleration of erosion via thermal abrasion [46], have been reported in the literature. High ice content and high content of fines in the soil, composing coastal bluffs and nearshore are typically found in the coasts prone to the thermal abrasion. These factors favor (in the presence of wave action on the bluff) high erosion rates as they do not provide beach-forming material, which would play a protective role against wave action. Complete attenuation of thermal abrasion when the coast was protected by grounded ice ridges (stamukhas) was observed by [46].

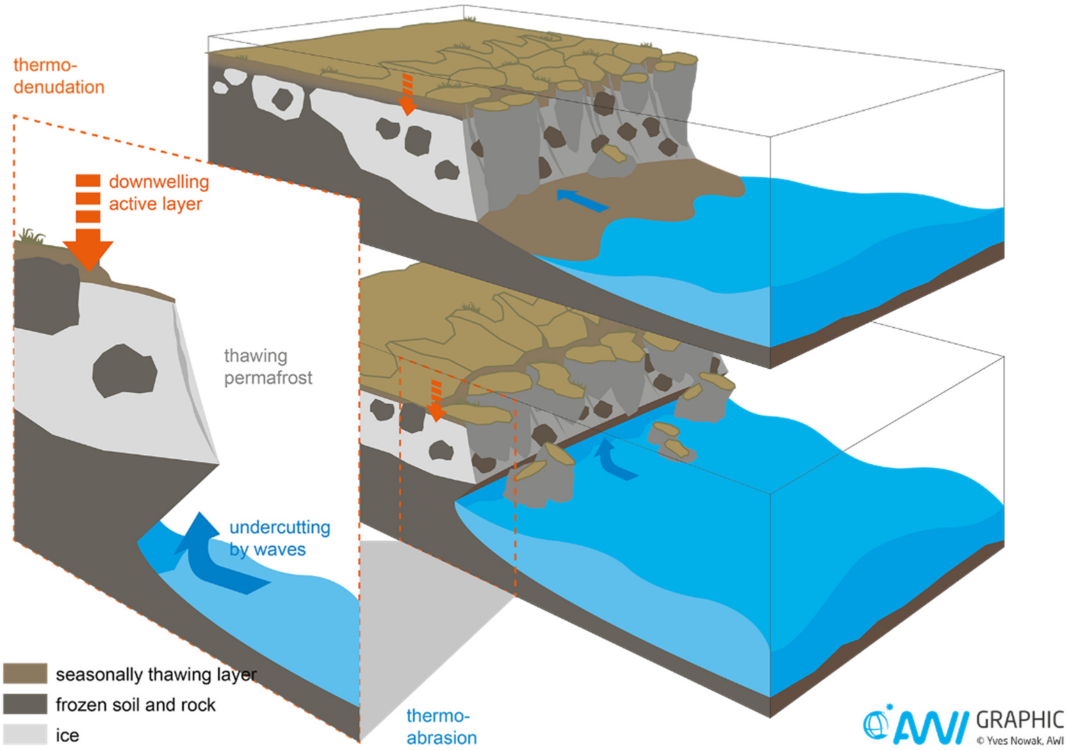

Figure 2. Illustration of thermal abrasion and thermal denudation (Copyright: Alfred-Wegener-Institut / Yves Nowak, CC-BY 4.0).

Thermal abrasion causes the development of the secondary processes, [46]: thermal settling of the sea bottom and thermal denudation of shore cliffs (Figure 2). Thermal denudation is defined as the combined influence of the energy balance at the ground surface above the waterline, [46]. Hence, thermal denudation is related to a suite of subaerial slope processes in permafrost conditions, which are mainly represented by soil mass movements in permafrost. It is usual to observe the development of thermal denudation during summertime. Products of thermal denudation are afterwards removed during autumn storms accompanied by surges. The naked coastal bluff is then exposed to wave action, "activating" thermal abrasion. Thermal denudation may cease in the absence of storms with surges. It can be possible that thermal denudation is the "prevailing" process during several years, when large storms with surges are absent. But the next large storm event can change the erosional regime from "thermal denudative" to "thermal abrasive", such situation was reported by Sinitsyn et al. [14]. Eventually, the coastal bluff will return to a "thermal denudative" regime in the period following a large storm.

Thermal denudation as a primary process. Thermal denudation can be a primary process, i.e. coastal retreat may also happen in the absence of thermal abrasion. Such a situation is possible in specific conditions with low bluffs composed of ice-rich fine-grained soil, with narrow or absent beach. Observations of such situation are presented for instance in [48]. An indication of such a situation (based on analysis of the wave data) is presented in [49]. One can find similarities between thermal denudation and calving process of glaciers, which strongly correlates with ocean temperature [50].

Protective role of level sea and other sea ice features. Sea ice limits wind action and restricts the wave energy reaching the coast for many months; [43, 51-54]. Ice can furthermore protect the shore by cementing the beach; [55]. A relationship for assessment of the influence of sea ice concentration on mitigating the wave energy is presented in [56] and verified by Ogorodov [55] based on field observation from Wadhams and Spuire [57]. Assessment of the influence of sea ice concentration on sediment transport in storm conditions is presented for instance in [58].

Processes of sediment transport by sea ice from shallow areas. Several processes contribute to this category, which details are presented for instance in [55]. Ice rafting is one of the processes which may cause significant sediment transport. Ice can contribute to sediment transport with the formation of frazil or anchor ice in shallow water [52, 59]. Sediment entrained into newly forming frazil or anchor-ice can later be transported by the drift ice on significant distances. Especially, sediment entrained by frazil ice can significantly contribute to the loss of shoreface sediments, [9]. More details and references are given in [9]. Ice rafting may be of particular importance for shallow and wide nearshore zones with fine-grained sediments (the western part of The East Siberian Sea, The Laptev Sea) [55].

Ice gouging. Ice gouging can be produced by icebergs (and other large features as ice islands) or ice ridges. Icebergs originate from glaciers with a sea front. Ice ridges produced via shearing, which may occur offshore between the fast ice and the floating ice, produce large pressure ridges with keels that can reach several meters in height. If moved, these keels can rework surficial seabed sediments and create ice gouges, also called ice scouring [52]. Gouges represent long, linear tranches. The amount of bottom sediment removed by keels of ice ridges may be significant, and hence, one may have to take it in account when defining a morphological change of the sea floor. The mechanical properties of sediments in the trough developed by ice ridge keels can be significantly different than the sediments of the berm on the sides of the trough. An estimate of the density and depth of ice gauges can be obtained from sonar scans of the seabed [60]. Repetitive seabed mapping can be instrumental for constraining ice ridge and iceberg scour frequency estimates, example of such works for offshore Labrador is presented in [61].

An engineering assessment of ice gouge statistics (the American Beaufort, Canadian Beaufort, and American Chukchi Seas) and recommended statistical distributions for extreme ice gouge parameter estimation are presented in [62]. The impact of environmental factors on the distribution of extreme gouging events (in the Canadian Beaufort shelf) is presented in [63]. Another important aspect when assessing ice gouges is the determination of their age, which forms a basis for the temporal statistics of ice gouges. An overview of quaternary dating methods can be found in [64].

Ice wallow. Ice wallow relief on the sea floor and on beaches is produced due to interaction of partly or fully grounded ice floes and currents/waves [65]. In the nearshore, such interactions produce irregular depressions and mounds up to 30 m in diameter and several meters in depth. Smaller, but similar features can be also produced on the beach. Wallow relief affects mobilization and transport of sediment. More details and references are given in [9].

Scours around grounded ice ridges. The scours occur due to hydrodynamic effects during interaction of waves and currents with grounded ice ridges. The scours may have dimensions of 3 m in depth and more than 50 m in diameter [55]. Similar process may happen in rivers due to interaction of masses of jammed ice and river flow, which may cause severe scour.

Ice bulldozing. Mounds and ridges can be produced by simple bulldozing movement of ice floes in contact with the sea floor. This process differs from gouging, where linear trenches are produced [9]. Another part of this process is depressions, which appears after stranded ice on the shoals when ice ridges melt.

Ice pile-up and ride-up (ice encroachment). Ice can act as a geomorphological agent when it piles up on the coast. This process may take place in any time of the year, but it often happens during spring and fall [66]. The duration of the process is usually short term (up to tens of minutes). The latter authors point out that the duration and strength of the wind are the factors controlling dynamics of the ice cover, but local winds cannot be relied upon for predicting these events, as some of them were observed in "calm periods". The former is supported by Taylor [67], who outlines that "the formation of grounded ice ridges and shore ice piles does not require abnormally strong forces, rather ridging can occur during moderate but sustained winds, … ice piles reach their greatest heights when tides are also attaining their maximum level". During this process, relatively thin sea ice (usually less than 50 cm thick) is pushed landwards, ice crumbles under pressure on the shoreface, where its pieces scoop the soil material. With further advance, ice mixed with sediment forms piles (up to 20 m). Melting of such piles, and smoothing them by wave action results in "elevating the barrier, and steepening of the upper shore profile" [9]. It is believed that such processes "are active out to 20 m water depth" [68]. Ice ride-up may propagate on several hundred meters inland and may cause severe damage to infrastructure. The prediction of ice encroachment events may be based on historical data obtained in similar site conditions, as presented in [69].

Ice-foot processes. Based on observations on rocky coasts, these processes can act as: i) a buffer protecting coastal cliff; ii) as processes causing disintegration of a coastal cliff and transportation of broken material by floating it away (this process is mentioned above among the processes of sediment transport by sea ice) [70].

Strudel scour. Typical process for river deltas before the ice breaks up. Melt water runs on the top of river/delta ice cover and eventually percolates through it, creating strudel scour at the places of percolation. Strudel scour may expose buried subsea pipelines. Strudel scour frequency and severity can be used to produce hazard maps for the assessment of risks associated with pipeline routing [69].

Aggradation of newly formed permafrost on tidal flats. This process takes place in the areas which actively aggradate; a description of the process is presented for instance in [21].

Seasonal freezing of the shore. This process "cements" the shore which makes it more resistant to wave action and ice wallow during storms in cold periods of the year.

Wave action of calving glaciers or icebergs on the coasts. The effects of this process were reported for unconsolidated clastic ("sandy") coasts (mainly on barriers). This process was also for instance observed at permafrost-affected cohesive shores [71].

Processes in sub-sea permafrost. In sub-sea permafrost the following specific processes are typical or may be encountered [37]: thawing from above (resulting in thermal settling of sea bottom) and thawing from below, freezing of sea bottom sediments in sub-sea conditions (several sub-processes), formation of separate ice crystals in the ground in specific sub-sea conditions, diverse submarine mass movements, processes associated with degradation of gas hydrates.

Processes affecting sub-sea permafrost at the shore and nearshore. Permafrost at the shore and nearshore is mainly affected by the following processes [37]: thawing from above (resulting in thermal settling of sea bottom) and thawing from below; sedimentation of eroded material; sediment resuspension and transport by wave action and by currents; sediment entrapment and transport by sea ice; processes associated with formation of bottom-fast ice (seasonal freezing of the bottom sediment through bottom-fast ice and injection of brines into the sediment).

Arctic-specific subaerial processes. Arctic-specific subaerial processes are not restricted to the coastal zone but may take place there. Subaerial processes include: soil mass movements in permafrost, gullying or thermal erosion, nivation, frost wearing (or cryoclasty), thaw settlement and thermokarst, frost susceptibility of soils. Thermal abrasion may to some extent be included in subaerial processes. As mentioned above, thermal abrasion represents block failure erosion generated by wave action on the lower bluff.

Soil mass movements in permafrost. Flow, slide and fall are the types of soil mass movements, happening under influence of gravity, that are present in permafrost [72].

Coastal process named as "thermal denudation" may include soil mass movements of the types "flow" and "slide". Thermal denudation is the process which shapes features known as "retrogressive thaw failures (RTF)"/"retrogressive thaw slumps"/"thermo-cirques" and "thermo-terraces". This spectacular phenomenon is typical for ice-rich permafrost containing excess ground ice in form of massive ice. Massive ice may be present in the form of instrata sills (or ice beds) or ice wedges which are exposed in retreating headwalls [19]. Mudflows form the transport sediment from retreating amphitheater basins downslope to the shore. Retrogressive thaw slumps are a form of backwasting thermokarst, often initiated by coastal erosion [73]. This phenomena is described for instance in [74-77]. Qualitative link of retrogressive thaw slumps and coastal erosion is presented in [74, 78, 79]. Climatic controls are the most important factor defining the slump activity [80]. Retrogressive thaw slumps of large C-shaped failures take place on coastal sections where ground ice is present in form of large pure ice bodies. In contrast, distinct thermo-terraces form in conditions where thick ice wedges are present. Stabilization of retrogressive thaw slumps and thermo-terraces take place when the thickness of the deposited thaw material exceeds the active layer thickness. This paragraph is based on [25].

Thermal erosion. Thermal erosion refers to the complex of erosional processes that are associated with running water acting upon ice-rich permafrost [81]; [82]. Typically, thermal erosion results when surface runoff from snowmelt, summer precipitations, or thawing permafrost, becomes concentrated along ice wedges, causing potential thaws. It is sometimes referred also as “fluvio-thermal” erosion. Overduin et al. [25] use the term "thermal erosion" as one embracing both, thermal abrasion and thermal denudation. In this case "thermal erosion" incorporates "the effects of wave abrasion, sediment transport along and across the shoreface, the formation of thermo-terraces, landward thawing of the coastal bluff and water-borne transport of material from the bluff towards the beach owing to melting of ground ice" [25].

Nivation. It has been recently observed [83] that nivation is another Arctic specific parameter influencing erosion of coastal bluffs. The concept of nivation was defined in 1900 by Matthes [84] as the process of backward erosion at the steeper portions of a snowdrift site caused by freeze-thaw at the edge of the snowdrift, with the subsequent loosening and downward transport of loose material. Nivation is linked to the presence of a snowbank forming on the lee side of the coastal bluff by recurrent wind blowing the snow over the bluff crest. The presence of this snowbank influences the failure mechanisms by changing the thermal regime of the bluff and by mechanically dragging particles down the slope during surface wash. The thermal regime, with lateral (retrogressive) permafrost degradation, is of importance where the failure of thawed sediment recurrently exposes the permafrost table to thermal degradation, leading to a retrogressive mass movement and failure. Nivation backwall failure processes have been described from terrestrial nivation sites such as NE Greenland [85]. Nivation backwall failure processes triggered during late spring and summer, as described from Greenland, are primarily caused by the complete saturation of the very shallow active layer in the upper part of nivation hollows. The saturation stems from the inflow of meltwater that drains downwards from the above located much thicker active layer [85].

Frost weathering. Frost weathering or cryoclasty is an important process that occurs in lithified Arctic coasts. Frost weathering is driven by the temperature-dependent wetting and drying of the ground [86]. During wetting, crack and cavity in rock or soils may fill up with water. During freezing water expands its volume by 9% to create ice. The stresses created by this expansion in a limited space create a jacking on the rock or soil. This process is also named frost shattering or frost wedging. Specific triggering mechanisms and relevant meteorological factors corresponding to rockfalls occurrence (for limestone conditions) are presented in [86]. Such mechanisms are practically identical for coastal cliffs; hence they can be utilised for assessment of dynamics of rocky coastal cliffs.

Thaw settlement. Ground ice of several forms (coatings on soil particles, ice inclusions and ice lenses, ice wedges, ice with soil inclusions) can be found in frozen ground. The resulting phenomenon on thawing is thaw settlement as ice disappears and the soil skeleton must adapt itself to a new equilibrium. The differential melting of ground ice in permafrost leads to a variety of surface features falling under the term thermokarst (mounds, caverns, disappearing streams, funnel-shaped pits, elongated troughs, and large flat-floored valleys with steep sides). A disruption of the permafrost thermal regime may occur due to broad-scale climate or local environmental changes. This section in based on [36], Ch. 4.

Frost susceptibility of soils. The frost susceptibility of a soil is defined in terms of its frost-heaving and thaw-weakening behaviour. Several schemes exist to classify soils on frost susceptibility properties. These properties are required for designing foundations and pavements. This paragraph in based on [36], Ch. 2.

Coastal terminology of the SAMCoT Guideline

The definition of coastal zone presented in the *CEM* is used as a basis in the TG: "A coastal zone is defined as the transition zone where the land meets water, the region that is directly influenced by marine or lacustrine hydrodynamic processes. The coastal zone extends offshore to the continental shelf break and onshore to the first major change in topography above the reach of major storm waves". The coastal zone is subdivided into four subzones:

- Coast
- Shore
- Shoreface
- Continental shelf

The definition provided in the *CEM* is wide, and it seems reasonable to limit/modify the limits of the coastal zone considered in the TG. This have to be done bearing in mind the boundaries of coastal processes and phenomena and technological particularities which may affect the infrastructure in permafrost-affected coastlines or in coastlines in cold climate. These considerations are (without priority):

1. Flood limit due to a severe storm
2. Presence of sea ice features and processes
3. Particularities of permafrost regime
4. Corrections due to results of coastal processes
5. Depth of closure
6. Typical coastal structures and some limits due to technological requirements
7. Considerations regarding the Continental shelf

The following subzones within the coastal zone are suggested and defined based on points 1 to 7:

Coast

The landward boundary is defined by the farthermost landward extent of the following phenomena, characterized by acceptable low probabilities[3] or the permafrost conditions: (i) storm with surge, (ii) ice storm with surge, (iii) sea ice phenomena (as pile-up and ride-up (i.e. ice encroachment) or ice storm with surge), and (iv) "temperature boundary" for permafrost.

Shore and shoreface

Seaward boundary of this subzone is defined by the farthermost seaward extent of one of the following conditions: (i) depth of closure (DoC), (ii) limit for dredging operations (LfDO), and (iii) belt of grounded ice ridges.

Offshore

Offshore may be part of the shoreface according to classification in the *CEM*. This subzone starts seaward from the "shore and shoreface" subzone. This zone ends where no actions of large ice ridges or icebergs can be expected.

Furthermore, sub-boundaries should be considered corresponding to each of the above-mentioned phenomena when defining the loads from them or performing modelling. As noted earlier in this document, sub-boundaries for thermal and chemical processes are presented in [35], and sub-boundaries for ice related processes and phenomena in [55, 87].

The suggested boundaries of the coastal zone and subzones are within the following subzones defined by *CEM*: (i) coast, (ii) shore, and (iii) some part of the shoreface or beyond it, covering some part of the transition zone between the shoreface and offshore. A detailed discussion about the influence of points 1 to 7 on boundaries of coastal zones is presented in the TG. A sketch of characteristic infrastructure elements for suggested boundaries of coastal zone of permafrost-affected coastlines is presented in Figure 3. Note that this is a general sketch, i.e. the boundaries may vary depending on ground temperature regime, coastal dynamics on the site, sea ice conditions, and the wave climate.

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[3] Such probabilities are presented for defining the ULS for extreme action in [17].

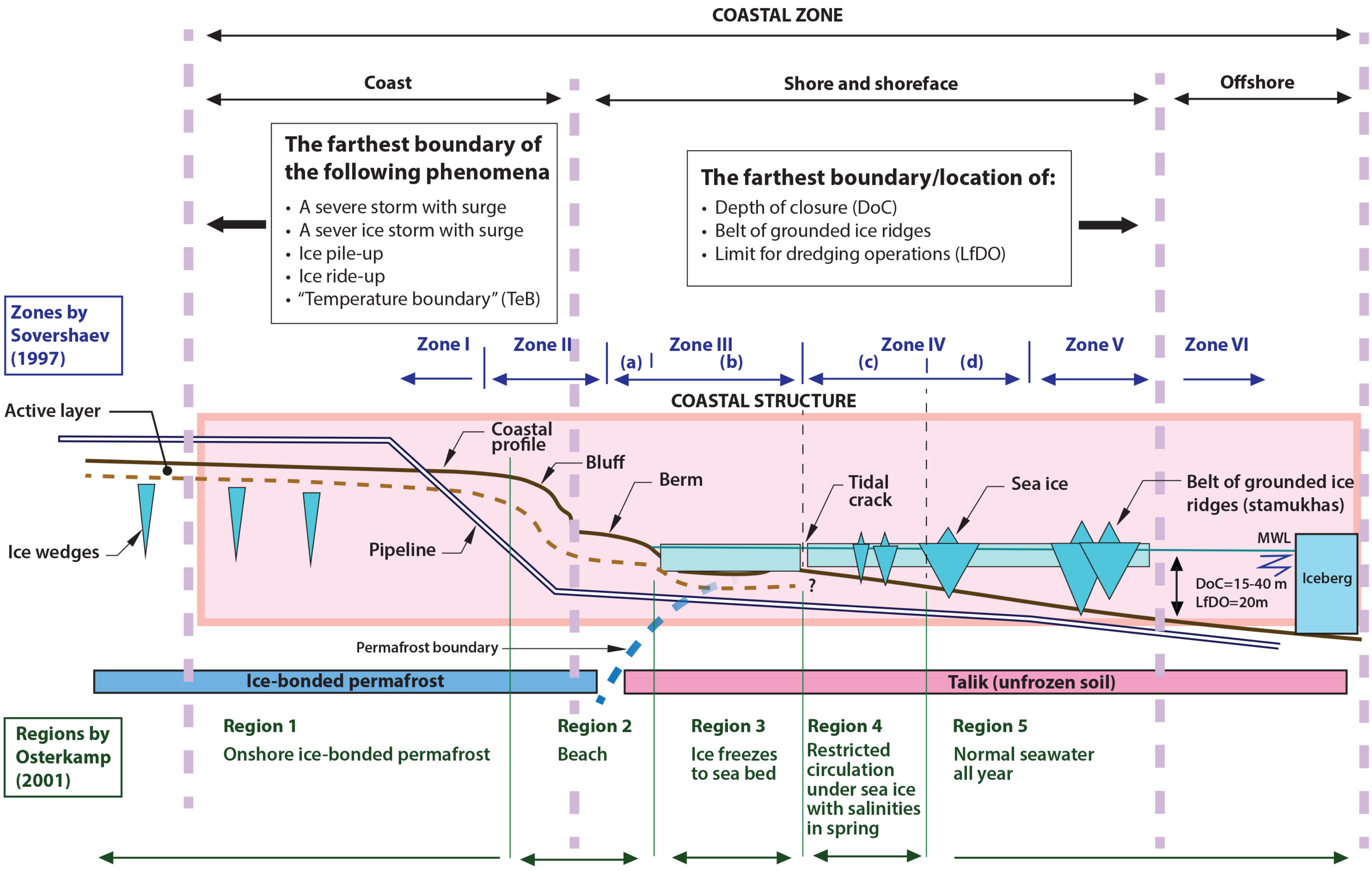

Figure 3. Sketch of an infrastructure in permafrost-affected coastal zone (after [35, 87])

Following the suggested boundaries of the coastal zone, one may add the following types of structures in addition to structures identified within ISO 21650:2007 [88]:

1. Structures to manage sediment transport, scour and beach stability (as groins)
2. Sea floor installations
3. Structures for pipeline and cable crossings
4. Artificial islands
5. Various gravity structures
6. Other civil and industrial structures located within the coastal area

Many other general types of structures may be located in the above-defined boundaries of coastal zone and could be called "coastal structures". In this perspective, general types of structures, which may be considered as "coastal structures" following the definition provided in this document are: bridges, buildings, roads, water barriers, pipelines, artificial islands, platforms, rain tracks, cable and pipeline shore approach/shore line crossing, cables, and wind turbines.

Site investigations

Site investigations provide the basis for designing coastal infrastructure. Site investigations for coastal infrastructure normally include the following:

1. Map data
2. Geological and geotechnical investigations
3. Metocean data
4. Ecological investigations
5. Other types of investigations (archaeological, sociological, etc.)

There are few guiding documents available for conditions of the cold regions compared to documents for temperate climate. This is especially true for the Arctic region. The reason being a lower level of knowledge on the environmental processes and phenomena, few numbers of projects and lesser experience.

The TG presents a summary on recognized practices for site investigations. Focus was placed on geological and geotechnical investigations, as well as metocean data. It is assumed that these types of investigations have most particularities in cold climate environments compared to temperate climate. The differences hence shall be clearly understood, especially by engineering personnel entering design in cold climate for the first time.

The following "families" of recognized practices were summarized or identified:

1. International – ISO, DNVGL, WMO
2. Europe – Eurocode 7
3. North America – USA and Canada – ASTM, UFC, CEM, BNQ, and other relevant practices
4. Russia – SP, and other relevant practices

A description of geotechnical site investigations is presented in the TG. The following features are covered:

1. Generalities for geotechnical investigations
2. Onshore site investigations (field test, sampling methods, laboratory tests) of unfrozen and frozen sediments, including method overview in the standards (ASTM, GOST, ISO) and other practice
3. Offshore site investigations in unfrozen sediment and sub-sea permafrost

Seasonal frost penetration and permafrost are among the factors defining the cold regions. These factors are studied within the geocryological survey. A summary on existing practices for geocryological survey is presented in TG, the summary covers the Canadian, Russian, and USA practices.

An overview of metocean and ice data for design of infrastructure in the Arctic is presented in the TG. The overview is based on considerations of ISO and other references.

Map data (topography and bathymetry) is not presented in the TG as it is a standard type of data.

Lithodynamic investigations comprise an important part in site investigations for coastal projects. An outline of lithodynamic investigations and references are presented in the TG. These investigations focus on sediment type and its dynamics due to waves and currents. Lithodynamic investigations may provide input data in- and data for verification of modelling coastal processes. The outcomes on lithodynamic investigations [89] are:

1. Plan (in plan) deformation parameters of the beach and submarine coastal slope (limits of erosive and accumulative zones)
2. Yearly and long-term (multiyear) changes of beach and submarine coastal slope
3. Forecast of the amplitude and intensity of deformations of beach and submarine coastal slope (in the plan and vertically)
4. Sediment budgets

Investigation methods for sediment transport in the littoral zone are: study of bathymetry surveys, aerial photos and images from LiDAR, differential SAR Interferometry over time, direct measurements (as for example current meters, CTD probes, turbidimeters, bed load traps, bedload sensors or optical backscattering sensors), direct measurement of turbidimeter, bio-optical sensors and in situ laser grain size meters with so called gliders (an Autonomous Underwater Vehicle), measurements of sedimentation volume by a manmade blockage, video-based studies.

The assessment of coastal dynamics is an important procedure for facilitating site selection for coastal projects. References to techniques for temperate climate and detailed analysis of several studies for assessment of coastal dynamics in the Arctic are presented in the TG. Based on the former analysis, commonly used methods for assessment of coastal dynamics in the Arctic are outlined in the TG. Main types of surveys are:

1. Onshore surveys to study shoreline change, change of coastal bluff (linear), bluff erosion (volumetric). The following methods may be applicable: spot measurements, transects by optical surveys, topographic surveys (optical theodolites and laser total stations), DGPS surveys, photo points, time-lapse camera, videography, laser scanning, structure from motion, ground surveys for support of remote sensing, historical data of other types (visual observations from the vessels, knowledge of local people, "driftwood limit" as an indicator of flooding due to storm surges).
2. Offshore surveys to study shoreface profiles and change of shoreface profiles. Bathymetry surveys with echo sounding (single and multibeam) and side scan sonar profiling may be applicable.
3. Remote sensing to study shoreline change, crest of coastal bluff change, shoreline delineation. The following methods may be applicable: comparison of imagery from different dates and analysis of high-resolution digital elevation models (DEM). Sources of imagery: conventional aerial photography and video, high-resolution satellite images, airborne laser altimetry (LiDAR), synthetic aperture radar, navigational and other maps, historical records.

Further, references and considerations for assessment of specific Arctic coastal processes are provided. Coastal processes can be represented on hazard maps, references to existing hazard maps for Arctic coasts are also provided in the TG, summarizing particularities of the content of hazard maps focused on coastal issues. Simple indicators (geo-morphological and hydrometeorological) for prediction of coastal behaviour (stable vs erosive) are presented in the TG. References for finer analysis based on computational tools are provided.

Arctic constrains for data acquisition and planning

There are specific constraints for data acquisition campaigns for site investigations and other operations in the Arctic. The TG provides an overview on the following matters:

1. Main factors and their consequences affecting field works in the Arctic, and countermeasures
2. Timing for specific data collection
3. Accessibility of the sites and overview of means of transportation

4. Suggestions for instrumentation

Several other factors important for the site investigation include (but not limited to): HSE routines, including safety routines associated with approaching/entering/being/ assisting/leaving/ in handling different means of transportation; detailed planning of specific field works depending of season (geotechnical works, sedimentological, data collection of weather data, hydrological works); routines related for organization of field works, such routines are related (but not limited) to polar bear protection, planning of nutrition for field camp; handling of unexpected situations (extreme weather conditions, unexpected weather conditions, fails of equipment, unexpected geotechnical conditions, personal interaction in the group and with local inhabitants, local industry.

Types of data, which can be acquired by means of remote sensing

Fieldwork for site investigations and for other needs during the project are normally associated to high costs, as well as to safety and environmental issues. Such limitations can be overcome by remote sensing, which provides opportunities for collection of several types of data. The TG provides introduction to remote sensing and its applicability for data collection in temperate and cold regions.

A number of variables for the atmospheric, oceanic, and terrestrial domains can be observed by the remote sensing. Applicability of data collected by means of remote sensing to engineering purposes is not obvious and shall be verified prior to inclusion of it into considerations for the needs of the project. In particular, the following data can be collected:

1. Marine hydrological data (waves, surges, tides, long-term dynamics of sea level, sea water temperature)
2. Sea ice data (such as sea ice extent and concentration, sea ice thickness, sea ice type, sea ice drift, and other parameters)
3. Shoreline change
4. Assessment of land subsidence and subsidence of structures
5. Extend of flooded areas during spring flood
6. Small scale river hydrological data

Remote sensing in cold regions can serve in particular to two goals:

1. Remote identification and mapping of surface features (shorelines, thermokarst lakes, pingoes, ice wedge polygons), including their changes in time and displacements
2. Remote sensing of physical variables which directly or indirectly relate to thermal surface conditions (such as land surface temperature or freeze-thaw state of the surface)

There are, however, several particularities in remote sensing which need to be considered in high latitudes and permafrost investigations.

Methods for remote sensing of mountain permafrost, lowland permafrost, and physical variables related to the thermal state of permafrost are presented in the TG. Further, several examples of important permafrost features, processes and variables which were assessed by remote sensing in permafrost regions are presented in the TG.

Approaches for Multi-criteria analysis in locating coastal structures

The selection of the optimal location for coastal structures can be performed by using Multi-Criteria Decision-Making (MCDM) process. An MCDM process encompasses all involved parameters and their relative importance in the decision process. The outcome is a "ranking" of the different project alternatives, considering the interests and preferences of the multiple stakeholders.

The TG provides references and describes some commonly used MCDM methods. A description of case studies when MCDM methods were used to route subsea pipelines and to define port location is presented in the TG. SAMCoT's example for selection of a pipeline landfall location in Artic conditions is presented in the TG.

Recommendations for the development of sustainable coastal infrastructure

The development of coastal infrastructure in the Arctic should ideally follow the principles of sustainability, which aim to address today's needs and the impacts on future generations. Sustainability provides a holistic view that is often comprised of three main pillars: ecology, economy and society [90]. The three main pillars of sustainability can be further expanded and explained through sustainability indicators (e.g., technical aspects, impacts on land and water, and health and safety) to capture the effects of relevant parameters on sustainability. The number of pillars and the corresponding sustainability indicators are problem-dependent.

The development of sustainability indicators for coastal infrastructure has not been examined explicitly to the best knowledge of the authors. However, several useful and relevant sustainability indicators have been already developed for other types of infrastructure, buildings, civil engineering projects, and coastal areas, as presented in the TG. Sustainability indicators that are potentially relevant for Arctic coastal infrastructure are categorized below with respect to the sustainability pillars. The indicators are adapted from the SUSTAIN [91] and SuPerBuilding projects [92], both presented in detail in the TG.

Environment

Coastal erosion, length of artificially defended coasts, impact on the ground thermal conditions, climate change effects, greenhouse gas emissions, hydrocarbon spills, consumption of renewable and non-renewable energy, energy consumption, use of water, water pollution, wastewater production, construction and demolition generation of hazardous and non-hazardous waste, ground sealing, change of land use, impacts on coastal and marine habitats.

Society

Demographic conditions, poverty, educational structure, crime, safety, policies and strategies for sustainability, stakeholder involvement, management practices, monitoring tools.

Economy

People and assets at risk in erosion prone areas, life cycle cost, capital cost, operational costs, unemployment rate, employment by sectors, transport usage, transport of goods, tourism.

The TG presents an overview of relevant research projects and initiatives for sustainable built infrastructure.

Considerations of Climate Change

Climate change scenarios, trends and projections

An increasingly large number of scientific studies and publications have unequivocally indicated that global climate has been and will continue changing for the coming several decades. Records show that atmosphere and ocean have been warming, snow quantity and ice covers have been decreasing, sea levels have been rising, and the concentrations of greenhouse gases have increased. The main physical drivers of climate change are natural and anthropogenic substances (e.g. CO_2, CH_4, N_2O etc.) that alter the Earth's energy budget.

The main variable in predicting climate change is the trajectory of future greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC), based on findings from the scientific community, introduced new scenarios for future greenhouse gas emissions known as Representative Concentration Pathways (RCPs) [93]. The RCPs provide time-dependent projections of atmospheric greenhouse gas concentrations. Four pathways are defined with different emission characteristics: (i) RCP2.6 – low emissions, (ii) RCP4.5 – intermediate emissions, (iii) RCP6.0 – intermediate emissions and (iv) RCP8.5 – high emissions.

Based on the different emission scenarios and historical data, climate change models are used to project the trajectories of various climate phenomena. General Circulation Models (GCM), also known as

Global Climate Models, are used to generate climate trends and projections. Based on these models and historical data, global projections of various climate phenomena (temperature, precipitation, sea level, sea ice, snow cover and frozen ground, storms and waves, oceanic acidification) are made for different emission scenarios. Besides the general trends and projections, the frequency of climate extremes (such as temperature extremes, heat waves and warm spells, precipitation extremes, floods and droughts, and extreme sea levels) is expected to increase associated with climate change. It should be emphasized that future projections of climate change are not like weather forecasts. Deterministic predictions are impossible, making climate change predictions uncertain.

GCM results are obtained at global or continental scales for climate conditions averaged at monthly, seasonal, annual or longer time frames. To make regional and local climate predictions, downscaling based on information known at global scales is required. Downscaling is a term usually used to describe a process where climate information is obtained at spatial scales finer than 100 km by 100 km and temporal scales finer than monthly values.

Impact of climate change on infrastructure

The impact of climate change on infrastructure may vary from very low to severe depending on its sensitivity to various factors. Some factors are the lifetime of the structure, level of over-design or safety margin, changes in ground surface conditions and sensitivity of permafrost to temperature changes. Impacts of climate change on permafrost, stability and maintenance of transportation routes, coastal erosion, and industrial development are among the topics which are normally discussed in relation to infrastructure in the Arctic. Typical structures on which effects of climate change are normally evaluated are pipelines, pile foundations, tailings, off-road transportation routes, riverine and offshore structures, open-pit mines, and waste storage facilities.

The evaluation of projects concerning potential impacts of climate change should be performed using risk-based methods. The objectives of *project screening* through risk-based assessment are to:

1. Ensure that projects with substantial impacts are duly scrutinized with respect to climate change effects
2. Allow projects with low climate change sensitivity and without potential for severe consequences to forego detailed analysis of climate change impacts
3. Provide guidance for project scrutiny by regulatory bodies and review panels

Risk-based assessment or screening of projects involves two main parameters: (i) *likelihood* – the sensitivity of the project to climate change, and (ii) *consequences – a* qualitative measure of the significance of an induced failure. The input required for the screening process includes information such as project purpose description, location, temporal scope, situation with respect to inhabitants, the natural environment, and its socio-economic value.

The main steps involved in a risk-based impact assessment on the effect of climate change are:

1. *Identification of relevant failure modes* for temperature changes induced in permafrost
2. *Categorization of climate change sensitivity* for the infrastructure type and ground conditions
3. *Combination of failure consequence* (negligible, minor, major or catastrophic) *and sensitivity* (low, medium or high) to determine the considerations required in design

Based on the result from these three steps, the level of climate change consideration required in design may be (i) no action required, (ii) qualitative analysis or (iii) detailed quantitative analysis based on the climate change parameters involved. Analytical and numerical modelling tools may be used for analyses depending on the required type of analysis.

Part II. The Prospect Stage

Introduction to the PROSPECT STAGE

The main goal of the Prospect stage is **to select an area for the structure**. This can be the "less affected area" in relation to natural hazards and impact of hydrometeorological features.

The following tasks should be performed to achieve the objective:

1. Obtain a general overview of a coastal zone[4], i.e. to benchmark *the main features* representing site conditions (data set at the Prospect stage), such as:
    a. Topography and bathymetry
    b. Geology and cryology
    c. Coarse estimate of hydrometeorological and ice features
    d. Coarse estimate of natural hazard processes and phenomena
2. Perform selection of an area for the structure via existing approaches

Benchmarking of the main features should be performed in the form of a data set. A data set for the prospect stage is suggested in the TG. The selection of the site should take into account an assessment of projected climate change impact(s) on the main features representing site conditions. This should be performed and included in the data set.

A data set for the prospect stage should be suitable for the use in approaches intended for site selection. At the same time, the data set shall be sufficient for defining the principal approach(es) for design of the structure(s) in the area. In general, the type of structure(s) is not known at the Prospect stage. Anyway, the overall aim of the project is known, and can be for instance:

1. Logistical hub or port
2. Facility for transhipment of natural resources from onshore to offshore (on vessels)
3. Shoreline crossing by pipeline or cable

Some other factors may influence the site selection (as ecological, archeological, social, availability of materials, transportation access, fresh water supply, other factors, etc.). Incorporation of such factors is possible via multi-criteria analysis.

The selection of an area for the structure (or site selection) may be based on one or several approaches. The following different approaches are currently in use:

1. Comparative analysis between several defined locations (or routes for linear structures). This approach is used by [94, 95].
2. Site selection based on it's suitability for infrastructure. These approaches is presented in [96] and based on processing of remote sensing results. The method is used for onshore infrastructure, and includes general, regional, and localized analysis of the area, which are followed by a ground survey.
3. Multi-criteria analysis, described in the TG. This approach is also a comparative analysis, which in general words allows a more detailed accounting of alternative locations or detailed screening for the best location. The selection is powered by mathematical relationships.

Planning and design process for coastal projects presented for instance in the *CEM.*

Approaches and variables for site selection may depend on the type of infrastructure to be constructed. Typically, the need to implement multi-criteria analysis arises for infrastructures whose locations are not obvious to define due to numerous acting factors (physical, social, environmental, cultural, etc.). The task becomes even more complicated when the infrastructure has elements spread in different coastal sub-zones (see Part. Ch. "Coastal terminology of the SAMCoT Guideline"), where various features are present (geological, cryological, hydrometeorological, and natural hazards).

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[4] According to the SAMCoT definition provided in PI., Ch. "Coastal terminology of the SAMCoT Guideline".

At the present time, tools for planning of infrastructure in the Arctic are mainly developed for the onshore conditions. Such tools, for different scales, are summarized in Part II.

In the prospect stage, the designer may assume that the site selection can be constrained by an actual location of a hypothetical field with natural resources, or a field where renewable resources are harvested. Hence, there will be a "critical radius" from such field to the location of the coastal infrastructure whose development is under consideration. The extent of the "critical radius" may be limited to the level of technological development and economical constrains at a given time period. Estimation of "critical radius" should include "far-field" considerations discussed in [97]. Data collection is performed across the coastal zone.

The *main features* shall be identified, characterized and forecasted due to climate change projections in the sub-zones of the coastal zone, where construction of the structure/elements is foreseen. Some of the features may experience certain variations across the coastal zone. This shall be taken into account when applicable (for instance when defining wind speed or air temperatures).

The dataset should be collected based on a probabilistic, risk-based methodology when applicable. The parameters for *the main features* may be obtained, for instance, by following/taking into account the ISO standards to the parameters of physical environment. ISO [97] provides recommendations on methods and recommends definition of (i) normal conditions, (ii) long-term distributions, (iii) extreme and abnormal parameters, and (iv) regional aspects.

The dataset should be collected in a GIS environment. Grid size may vary for different main features but shall be sufficient to represent sensible variations of the features. Data representing geology and geocryology, topography and bathymetry, hazard processes and phenomena should be collected on a geocryological map in GIS format. Such geocryological map shall cover the whole coastal zone. Requirements for sub-sea geocryological maps were not identified, hence, it is suggested to refer to existing mapping of sub-sea permafrost. One may suggest to collect data on hydrometeorological and ice features also as layers in the "geocryological map". In this case such map shall be called differently (for instance "hydro-geo-cryo" map).

Due to cost and time constraints, it is recommended to perform data collection in the following sequence:

1. Literature review (data sets and archives of raw data)
2. Interviews with locals
3. Simulations (hindcast via reanalysis) and modelling for hydrometeorological features (if needed)
4. Remote sensing means
5. Site visit
6. Field campaign

The following selected codes are fully or partially applicable, or may be useful as reference documents for the site selection at the prospect stage:

1. International practice: ISO standards [97-101], basically applicable in the way of data collection and detection of natural hazards.
2. Russian practice: SP 47.13330.2012 – Engineering survey for construction. Basic principles [94].
3. USA practice: 1) The Coastal Engineering Manual of the US Army Corps of Engineers [8] in conjunction with ER 1105-2-100 [102]; 2) Coastal and Harbor Design Procedures Manual [95] in conjunction with ER 1105-2-100 [102]; 3) UFC 3-130-02 – Site Selection and Development: Artic and Subarctic Construction [96].
4. Europe: Guidelines for the use of metocean data through the life cycle of a marine renewable energy development [103].

Hazard maps and other tools for planning infrastructure

Hazard maps may be utilized for planning of infrastructure at the prospect stage. Hazard maps, however, cannot substitute site-specific engineering design studies. A hazard map for the project shall represent all relevant hazardous processes and phenomena present in the area. In general, a hazard map shall cover all parts of the coastal zone, i.e. sub-zones of offshore, shore and shoreface, and coast. For the terrestrial setting, hazard maps are usually derived from comparisons of aerial photography or satellite products but may utilize results of field surveys and various types of modelling.

The following maps representing various hazard phenomena can be found in the literature:

1. Maps representing coastal erosion, based on field measurements or hypothesis-driven assumptions
2. Maps with risk of coastal flood
3. Maps of river flooding
4. Maps with risks of mud-flows, rockfalls, and avalanches
5. Maps of various permafrost hazards.

The presence of sub-sea permafrost can be considered as natural hazard. Hence, distributions of sub-sea permafrost and other hazards processes and phenomena in shore and shoreface, and offshore can be performed in a form of hazard maps.

Other tools, which may be applicable (at least at some degree) for planning infrastructure are:

1. Thaw sensitivity maps
2. An integrated, multitechnique, multidisciplinary approach [104]

The need in adaptation solutions of foundations due to climate change and human impacts (as part of infrastructure development) should be identified on this stage. General project considerations and strategies, and a risk-based impact assessment are presented in the TG.

Data needs at the Prospect stage

Data needs at the Prospect stage include the following categories (details are provided in TG):

1. Map data
2. Geomorphology, geology, geotechnics and cryology
3. Hydrometeorological and ice features
4. Hazard processes and phenomena
5. Structural performance
6. Vegetation
7. Other relevant considerations

PART III. THE DESIGN STAGE

Introduction to the DESIGN STAGE

The design of infrastructure is performed at the design stage. The TG present the following matters:

1. Assessment of coastal dynamics, including permafrost-affected coastlines
2. Engineering considerations for foundation design in permafrost areas
3. Models for thermal, hydraulic, and mechanical processes in soils
4. Solutions for typical port infrastructure in Arctic conditions
5. Solutions for design of coastal protection
6. Solutions and considerations for pipeline design
7. Engineering challenges and considerations related to sub-sea permafrost

Guidelines to design other types of infrastructure (including typical onshore development layouts, which are normally not considered to be "coastal", but may be in the coastal zone, as roads, railway lines, aircraft runways, etc.) are not presented in the document.

The site location has already been defined at the prospect stage. Also, the principal solution(s) for the structures are chosen. The planning and design process for coastal projects is presented for instance in [8]. Solutions, considerations, and selected codes for infrastructures mentioned above are presented in the TG.

A dataset for site characterization and design of specific infrastructures in the selected area is required. This data set shall cover all parts of the infrastructure in the area, which may be spread across entire coastal zone. A general dataset for designing infrastructure in coastal zone of permafrost-affected coasts and coast in cold climate is suggested in the TG, and summarized in the following chapter. The data set covers data needs for definition of the following features:

1. Map data
2. Climate
3. Loads and actions
4. Ground properties
5. Hazard processes

Considerations for various types of site investigations are presented in the TG. Several codes are available to perform site characterization for structures design. A list of selected international and national recognized practices and codes is presented in the TG. Summaries of the main approaches of these codes are also presented in the TG. The summarized codes were chosen due to their applicability (direct or indirect) in coastal zones and in permafrost and cold regions.

Decommissioning and removal of the structure is an important aspect which also needs to be considered during the design stage. ISO ([105]) (under revision as for April 2019) deals with this topic. This is however not covered by the present document.

The collection of field data in cold regions and in the Arctic is normally constrained by harsh climate conditions and remoteness of the site. Arctic constrains for data acquisition and planning of fieldworks, operations, and other activities are presented in the TG. Some data can be acquired by means of remote sensing; possibilities for collection of such data are presented in the TG. It is recommended to develop of coastal infrastructure in a sustainable way. This is especially relevant for the fragile conditions of cold climates and the Arctic. It is suggested to address the topic of sustainability based on the existing state-of-the-art approaches developed for infrastructure in conditions of temperate climate, which are presented in the TG. Considerations on climate change are important for development of coastal infrastructure. This topic is presented in the TG. It should be considered to incorporate climate change in the design of infrastructure, and (if needed) adaptation solutions for foundation of structures.

Data acquisition at the DESIGN STAGE

The data needs at the design stage includes the following types of data:

1. Map data
2. Geomorphology, geology, geotechnics and cryology
3. Hydrometeorological and ice features
4. Hazard processes and phenomena
5. Structural performance
6. Vegetation
7. Other relevant considerations

Data obtained at the design stage is complementary to the data collected at the prospect stage. Site investigations for data collection are presented in the TG.

Data collection is performed across the coastal zone. The boundaries of data collection zone are based on the near- and far field considerations. The dataset should be collected based on a probabilistic, risk-based methodology when applicable. ISO standards provide recommendations on methods and recommends definition of (i) normal conditions, (ii) long-term distributions, (iii) extreme and abnormal parameters, and (iv) regional aspects.

Site investigations at the design stage normally include a preliminary site investigation and a main site investigation. Both types of investigations may use the same techniques and therefore also the same standards. The difference between the two investigation stages is that preliminary work is done in a stage when little or insufficient is known about ground conditions. The preliminary site investigation is used as a basis (along with information obtained at the prospect stage) for planning the main site investigation. The latter being often more focussed on structure specifics and geometry.

As part of preliminary site investigations, a preliminary site visit takes place. This site visit is used (but not limited to) to clarify the following:

1. Hazard processes and phenomena across the coastal zone (terrestrial hazards, coastal hazards (mainly coastal erosion and flooding), hazards in the offshore)
2. Collect data for characterization of quaternary geology and cryology. Assessment of critical soil parameters
3. Hydrology at the site (groundwater regime)
4. Other site conditions, which may have adverse impact on the project implementation
5. Other reasons (as availability of local construction materials, drinking water, etc.)

If there are several areas under consideration, the information mentioned above shall be collected at all of these project locations alternatives. The results of the site visit may have great impact on creating a comprehensive basis for the final site selection and developing a preliminary design. The preliminary site visit may utilize geophysical survey supported by in situ soil sampling.

Assessment of coastal dynamics

Coastal dynamics can be assessed with several approaches and different types of modelling. These are presented in the TG. The complexity and site specificity of most of the parameters involved in Arctic coastal erosion make any modelling approach challenging. Coastal modelling must be related to and limited by the time scale of relevance. The modelling time scale should be defined early in the research process.

Models are needed and have been used to predict coastal evolution at different spatial and temporal scales. Deterministic, probabilistic and statistic models have been applied to predict future coastal morphology. A useful model may enable to study the effect of varying the main controlling factors. Existing models present different levels of complexity, reliability and accuracy. Despite the considerable research effort in modelling coastal processes, little consensus has yet emerged on which methodology is best to use. The main goals for coastal modelling are predictions of the behavior of the shoreline (shoreline evolutions) and offshore bathymetry.

Two main types of coastal models can be outlined [106]: (i) physical models (run in wave tank laboratory or basin), and (ii) equation-based models. The latter including numerical models and analytical models. Equation-based models are widely used for engineering applications despite their shortcomings. In addition to physical and equation-based models, techniques based on field observations, qualitative modelling and past experience are advocated to be suitable for practical engineering applications [107].

It is expected that in the future reliable predictions may be based on numerical models complemented with judgment based on field experience [106]. Cooper and Pilkey [107] advocate a similar "composite approach" involving several tools such as geoindicators (geomorphological and sedimentological), direct field observations, remote sensing, and numerical simulations. Combining them provides multiple verifications and increased accuracy of predicted parameters. This approach was used in several studies, including the "Futurecoast".

Systematization of predictive models and tools for coastal evolution is presented for instance in [108]. A summary of that systematization is presented in the TG; main categories of predictive models and tools for coastal evolution include: historical trend analysis, process-based models, vulnerability mapping, geomorphological analysis, parametric equilibrium models, stochastic modelling.

The recommended optimal use of modelling tools during the development of a coastal project is the following (based on [109]):

1. Baseline studies of ocean and coastal conditions:
   a. Baselines description of wind, waves and tides, storm surges, and sea ice conditions in the area.
   b. Coastal classification.
   c. Description of littoral drift conditions.
   d. Equilibrium profile (if applicable) and orientation of shorelines.
   e. Description of variability of conditions mentioned above.
2. Development of alternative schemes.
3. Detailed design and environmental optimization via numerical tools.

Selected scientific programs and documents for the period 1996–2017 for assessment and management of coastal erosion are summarized in the TG.

Some popular software packages for coastal erosion modelling in temperate climates whose approaches and methods may also be relevant for the cold climates are presented in TG. These software packages include *XBeach, Delft 3D, WAVEWATCH III, MIKE 21, REEF3D.*

Considerations elaborated by SAMCoT for coastal modelling of permafrost-affected coastlines are provided in the TG. These considerations include the following:

1. Basic considerations.
2. Some limitations of exiting coastal models to describe evolutions of cohesive shores.

Basic considerations suggest that it is important to define type of the coast (cohesive shore vs clastic sediment beach) and the main processes responsible for coastal change including specific Arctic coastal processes; to perform qualitative assessment of coastal dynamics for the planned life length of infrastructure; selection of specific model(s) for coastal processes should be supported by experience of its successful use in the past; data collection should be suitable for data utilization in commonly used tools and specific models should they be utilized; modelling results should be benchmarked against the results obtained with more conservative tools such as qualitative assessment and extrapolation of historical observations; local anthropogenic activities should be taken into account if applicable.

Exiting coastal models describing evolutions of cohesive shores, especially in permafrost-affected settings are constrained with the lack of data, tests and process understanding, which impedes their realistic implementation and may leave an engineer with statistical approaches or even simple judgments based on a global geo-understanding of the mechanisms driving erosion to estimate the rates of recession [110].

A summary of Guegan [111] of approaches and models applicable for assessment of coastal evolution including conditions of permafrost-affected coastlines is presented in the TG. Models and approaches specifically elaborated for handling dynamics of permafrost affected coastlines are outlined. The following methods and approaches are presented:

1. Coastal evolution via extrapolation of historical rates.
2. Vulnerability mapping of permafrost-affected coastlines.
3. Models for thermal denudation.
4. Models for thermal abrasion.
5. Thermo-erosion models.
6. Morphodynamic models for Arctic coasts.
7. Other modelling approaches.
8. Notes on erodibility of frozen and unfrozen soils.

Engineering considerations for foundation design in permafrost areas

General considerations for foundation design in frozen ground

Frozen ground may be found as seasonally frozen or continuous/discontinuous permafrost. A seasonally frozen ground is mainly characterized by a certain layer of soil freezing and thawing annually. The frost penetration depth, which depends on the atmospheric temperature and whether structures is heated or unheated, and the presence of frost-susceptible soils are the key factors for foundation design in such case. In addition to the proper selection of foundation depth, necessary counter measures should be considered to mitigate potential heave effects.

Permafrost areas are characterized by an active layer that freezes and thaws annually overlying permafrost. The selection of a foundation method for permafrost areas depends on whether the soil is thaw stable or thaw unstable. Conventional temperate zone foundation selection approaches are applicable for thaw stable permafrost comprising granular soils or rock with very low ice content. For thaw unstable permafrost soils, passive or active approaches may be used. Passive methods maintain the thermal regime without consumption of energy and examples include the use of thermosyphons, elevated construction for enhanced air circulation and modification of surface materials. Active methods, on the other hand, consume energy to control the ground thermal regime. A typical example of this is artificial ground freezing.

Types of foundations and design principles

Shallow and deep foundation as applicable in temperate regions are used in frozen ground with the necessary structural modifications. In permafrost areas, the design of shallow foundations is governed by the thickness of the active layer; bearing capacity and settlement analyses determine the required size of the foundation. A shallow foundation may be placed in direct contact with the frozen ground under suitable conditions but usually a gravel berm with or without insulation is used. Large and settlement-sensitive structures on permafrost are usually supported by pile foundations, which could be made of timber, steel or concrete. Pile installation in permafrost depends on the soil type, thermal regime of the ground, pile type and available construction equipment. For axially loaded piles, the long-term adfreeze bond between the pile surface and the adjacent frozen backfill or soil makes the basis for design. Piles may be subjected to lateral loads which may originate from short-term loadings imposed during construction, seismic forces or wind, and long-term loadings imposed by structural components. Design methods for laterally loaded piles in frozen ground are adapted from unfrozen soil mechanics by introducing the effects of creep and temperature.

Construction considerations

Construction methods for foundations in seasonally frozen soils and permafrost must be considered in order to examine their effect on the design and performance of foundations. Some processes that may affect the design of foundation are:

1. Disturbance of the thermal regime of permafrost caused by construction may be minimized. A quick recovery of the thermal regime may be achieved through a properly planned design and construction procedure. Excavation should be avoided in permafrost as much as possible to reduce a potential disturbance of the thermal regime. In cases where excavation is required, the season, type of excavation equipment, and duration of excavation are important factors to be considered.
2. The possibilities and limitations of constructing embankments, fills and backfills must be identified in the design and construction process. Weather conditions and availability of construction materials are important elements in the design process for embankments and fills.
3. Protection of foundations from frost heave or thaw settlement *during construction* is often overlooked. When there are frost-susceptible soils, it is important that the foundation is protected until the backfill is in place or until heat is available if it is required to prevent frost action.
4. Snow and liquid water have wide-range effects on infrastructure in permafrost-affected areas. The functionality of drainage systems and management of snow accumulation should be performed according to design during the stage of construction and maintenance.

Foundation failures in permafrost regions

The three main causes of foundation failures in permafrost regions are: (i) poor assessment of the soil conditions at the site, (ii) errors in choosing a foundation design approach and procedure, and (iii) poor construction quality and poor maintenance. Using structures not according to their design may be another cause leading to failure of foundations in permafrost. One of the main causes of foundation failures in permafrost is the formation of deep thaw zones and severe differential settlement. To foundations designed using a passive approach, failure is not very often related directly to air and permafrost temperatures. These failures are not caused by permafrost thawing but rather by climatic effects on foundation materials in the active layer and in the crawl space.

Foundations in permafrost-affected coastlines

The main factors affecting foundation design in permafrost-affected coastlines are ground properties, permanent and variable loads, coastal processes, human impact and climate change. These factors must be closely analysed for the coastal, shore and offshore zones. Sources of variable loads for these zones include wind, waves and currents, ice actions, snow and seismic actions. For a proper design of foundations on permafrost-affected coastlines, processes that are hazardous for foundations must be identified and considered. Example of such processes or phenomena include: (i) active frost heave, thaw subsidence, solifluction, massive ice beds and cryopegs in coastal zones, (ii) coastal erosion, sedimentation, scour and iceberg/ice ridge actions at shorefaces and (iii) subsea thermokarst, subsea mass movements, flow of free gas and iceberg/ice ridge actions in offshore zones. Climate change and the human activities affect coastline foundations such as through permafrost degradation and intensification of coastal erosion. The potential consequences of these processes on foundation include excessive deformation of foundations and soil/structural failure.

Consideration of climate change in foundation design

In recent years, consideration of the effect of climate change on existing as well as new infrastructure has become increasingly important. A direct effect on the ground is an alteration of the ground thermal regime. Rising temperatures lead to an increase in active layer thicknesses, warming and degradation of permafrost, and thinning and disappearance of permafrost layers. These changes affect the mechanical properties of the ground through loss of bearing capacity, increased thaw settlements, and creep deformations. A warming climate with increased levels of precipitation may also alter the groundwater regime in permafrost areas, which may lead the groundwater flow to induce permafrost degradation. It is essential to consider these factors in the design of foundations in frozen ground.

Incorporation of climate change in the design of foundations requires regional or localized climate projections. Air temperature trends and projections are the required primary input for analysis and design. Other climate phenomena may be considered depending on the type of structure and its location. The level of climate change related analysis required in foundation design depends on the type and purpose of the structure and the sensitivity of the ground to climate change. Evaluation of ground thermal regime based on historical trends and projections through analytical and numerical thermal modelling gives insight into sensitivity of the ground mechanical properties to temperature changes. Depending also on the level of climate change related analysis and design specified for a given structure. Thermo-mechanical and/or thermo-hydro-mechanical modelling may be performed using analytical tools and advanced numerical modelling software. Conventional material and load factors in design may need to be reconsidered for application in such cases.

Climate adaptation of foundations through mitigative measures may be considered to decrease or eliminate risks on existing as well as new foundations. Some of the most widely used approaches in permafrost engineering to control the ground thermal regime include thermosyphons, artificial ground freezing, enhanced air circulation, foundation material modification, structural modification for permafrost thawing, and interception structures for groundwater, which may affect permafrost.

Models for Thermal, Hydraulic and Mechanical Processes in soils

It is possible to model the behaviour of permafrost using Thermo-Hydro-Mechanical models (THM models). THM models can be used in general to define: (i) thermal regime of permafrost, (ii) bearing capacity and settlements of foundations/ground, and (iii) slope stability. Therefore, such models are capable of accounting for the complex interactions within permafrost. There are three basic approaches/methods to couple the different processes in THM models:

1. One-way coupling
2. Fully-coupled
3. Loose coupling

Thermo-hydro-mechanical models describe processes in frozen soil mathematically, but due to their complexity it is very difficult to solve frozen soil related problems analytically without making simplified assumptions. Therefore, these THM models are implemented in a suitable software which solves the complex equations numerically. Selected popular software packages are presented in the TG.

Solutions and design of typical port infrastructures in Arctic conditions

Port outline could be considered as a product of the life cycle costing analysis (LCC) if it is applied for a project. Port outline shall provide design conditions concerning:

1. Wave climate (loads)
2. Ice loads
3. Depths

Ice management methods may influence the port outline.

Challenges when building Arctic infrastructure

The range and severity of Arctic conditions must be considered in site selection for any infrastructure. Factors like climatic, hydrologic, topographic, and geographic conditions must be considered for site selection in Arctic environments. Infrastructure along the Arctic coast must also consider flood hazard, coastal dynamics, sedimentation, actions and loads from sea ice, and drift of riverine ice (ice transported by rivers).

The seasonal changes with relatively short summers and long winters implies short construction periods for outside work, which can imply a high degree of expensive pre-fabricated constructions.

Future climate changes can affect sea ice presence and its parameters, permafrost conditions, areas prone to flooding, and coastal dynamics.

Port site selection

Focus should be given to combine functional requirements with location specific requirements and boundary conditions. An important aspect of terminal placement is the nautical layout for safe navigation, terminal access, and ease of (emergency) departure.

Different areas in the Arctic can be selected for port site location. Some restraints can follow the choice of port selection:

1. Bay – favourable for ports, but problems arise with ice
2. Delta – should be avoided as port location due to river flood and unpredictable sedimentation, and actions from riverine ice
3. Open coast – favourable with less sea ice or ice-sheets compared to bays, but non-favourable with respect to wind and wave forces

Site conditions

Prior to selection and design of a port knowledge of the different types of site conditions is required:

1. Water levels
2. Wind
3. Waves
4. Currents
5. Ice
6. Permafrost

The design of port structures shall obey to environmental loads. Methods for estimation of environmental loads are for example presented in:

1. ISO (International standards)
2. API (American codes)
3. CAN/CSA (Canadian codes)
4. SP (Russian codes)

A port should be located to give an optimal protection environment to infrastructure and operational activities at sea and land. Mitigation measures such as construction of protective breakwaters and/or construction of ice barriers may be required.

Principal port layout

Port layouts must consider different environmental conditions/challenges. In particular:

1. Coastal erosion at different parts of a port. Hence, protection measures are needed in different parts of port.
2. Sedimentation of channels. Arctic seas are usually shallow, hence dredging of channels is normally needed.

Principal engineering solutions for port structures

The port/harbour design in the Arctic areas follows to a large extent the principles used in designing harbours in temperate climate. The major difference for breakwaters and other harbour structures in Arctic areas is that in addition to wave forces breakwaters may also be subjected to ice actions.

The most common port infrastructures are listed below:

1. Cellular wharfs
2. Sheet pile walls (backfilled)
3. Piled wharfs with steel or concrete slabs
4. Piers of rock
5. Anchor buoys
6. Dredged cannels and other excavations
7. Concrete caissons (gravity structures)
8. Artificial islands

Specific design considerations for foundations of port structures

The design of foundations for port structures follows the same principles as for temperate climate. Additional considerations can be needed due to:

1. Thawing/freezing of soils
2. Permafrost
3. Ice actions

Thawing/freezing cycles of soils can deteriorate the bonding between particles and subsequently affect the strength and deformation properties. Measures can be taken to reduce the thawing. Building in permafrost requires knowledge of climate and change of climate, active layer thickness, permafrost properties and soil properties. Action from ice is the most specific design consideration for foundation of port structures in Arctic climates. Sea ice formations can appear as level ice, ridge and rubble fields and icebergs.

Specific design considerations for ports in Arctic conditions

Guidance shall be provided on Arctic challenges which can be encountered in a port layout:

1. Mitigation of adfreeze of ice to the front wall of quay structures.
2. Ice ride-up on a pier, on the shore.
3. Action of expanding of level ice on mooring structures.
4. Ice action inside of sheet-pile boxes (frost heave and thermal expansion of frozen soil).
5. Sources of sedimentation in Arctic environments (which lead to sedimentation at port structures).
6. Thermo-mechanical loads of sea ice can be applicable for a given structure.
7. Forces from drift ice in special cases as from drift ice from river.

Existing examples of port outline in Arctic conditions

The TG comprise a description of some specific port outlines in Arctic conditions, namely:

1. *Port Sabetta* is situated on the western shore of the Ob river at the Yamal Peninsula in the Russian Arctic. One design requirement was to have a water depth of 15 m to ensure safe access and manoeuvrability to large vessels in the port. The 15 m isobath is located about 7,5 km from the shoreline near Sabetta. The design of the port comprised a balance between factors such as dredging volume, protection from ice actions, length of structures, constructability, and safe manoeuvring in the port.
2. *The Kashagan development* in the North Caspian Sea is placed in shallow water (4 to 8 m) which favours bottom-founded gravity-based structures and islands. Ice interaction is the main environmental loading. The implemented solution was to build protection barriers designed for the prevailing ice drift direction around the artificial islands containing infrastructure for oil exploration.
3. *Port of Nome* is the regional trans-shipment hub for many Western Alaska communities. Nome's port is typically closed six months of the year when seasonal ice prevents vessel operations. During heavy southerly storms vessels are prevented from mooring at the docks because of wave actions. Future plan comprise extended moorage facilities protected from waves.

Considerations on accounting climate change impact on port infrastructures

Permafrost engineers must address the problem of preserving infrastructure under projected future climate conditions. The climatic trends should be assessed for key time-varying parameters, with specific consideration of air and water temperatures, as well as sea ice and iceberg presence. The projected trends in climate from the most recent climate science must be used to estimate any change in parameters for design. These parameters should be updated during long-lasting planning operations prior to commence of construction work.

The coastal zone presents the greatest challenges in a changing climate, where combined problems of increased wave action, sea-level rise, and thermal erosion have no simple engineering solutions. Climate change impact in port infrastructure should account for:

1. Water levels
2. Sea ice (sea ice cover)
3. Storms and waves

Diminishing sea ice and longer shipping season due to warming will likely lead to development of new ports and expansion of older ports in the Arctic.

The main gaps in knowledge are the lack of site-specific scenarios providing the probability of occurrence of various meteorological conditions (temperature, precipitation, wind, snow and sea-ice thickness and extent, waves, and erosion rates). Monitoring of infrastructure and the coastal environment is essential. Climate sensitivity analyses used in design should be updated based on monitoring of meteorological data.

Solutions and design for coastal protection

Coastal hazards and Infrastructures

Structures for coastal protection are meant to provide protection against coastal hazards. The following coastal hazards may take place in coastal zone of cold regions and be dangerous for infrastructure:

1. Coastal erosion and local scours
2. Coastal flooding
3. Ice pile-up and ice ride-up, ice gouging (these processes may also be considered as coastal erosion processes)
4. Land subsidence
5. Failure of protection measures
6. Sedimentation (which may follow extensive scour on neighbouring area) leads to decrease of water depth, causing navigation issues for vessels
7. Wind hazards
8. Sea level rise
9. Dune hazards, incl. development of transgressive sand sheets

The TG address the following hazards: (i) coastal erosion and local scour, (ii) coastal flooding, and (iii) ice-related hazards. Other hazards were not examined explicitly. The coastal erosion hazard may be considered as the biggest among all three. Several concepts were suggested to handling coastal erosion in temperate climate [112], these are: (i) coastal resilience, (ii) coastal sediment cell, (iii) favorable sediment status, and (iv) strategic sediment reservoir.

A safe operation of structures against coastal hazards (coastal erosion, coastal flooding, and actions of the sea ice features) may be provided by structural or non-structural protection measures.

Examples of structures affected by coastal erosion in the Arctic

Examples of structures, which may affected by coastal erosion in the Arctic include oil storage facilities, wellheads, residential buildings, land strips.

Design considerations for coastal protection

Design considerations for coastal protection include:

1. Water levels
2. Waves
3. Sea ice
4. Structure height and wave run-up
5. Protection against flanking
6. Foundations
7. Filtration and drainage
8. Construction materials
9. Toe protection
10. Human activities

In addition, there are also Arctic-specific design considerations. These are presented in the following section.

Arctic-specific design considerations

Arctic-specific design considerations are due to:

1. Cohesive shores: they are composed of soils with high silt and clay content. The main difference between cohesive shorelines and stable dynamic beaches is that once the material from a cohesive shoreline is eroded it is transported offshore. Cohesive shorelines do not accrete while stable dynamic beaches have the potential to erode and accrete. If the cohesive material has a high content of cobbles and boulders (e.g., glacial till), clay and silt particles are washed away leaving behind a “lag deposit” of cobbles and boulders. This lag deposit slows down the erosion process and reduces recession of the shoreline.
2. Groundwater and surface flow: Groundwater management should be considered in slope stability. The best management techniques lead to minimization of the amount of water in the ground. In permafrost areas, the groundwater flow is limited within the active layer. Additionally, in a coastal slope where snow accumulates on the lee side due to recurrent wind, the groundwater flow is also controlled by the geometry of the frozen soils. In addition to groundwater, surface water (e.g., rain and snow melt) affects coastal erosion through gullying and surface wash.
3. Thaw-induced slope instability: a thawing slope may be subjected to several conditions such as deformations due to thaw settlements, surface runoff erosion, downslope movements of thawed soil from sloughing or ablation, and landslides induced by thawing soil.
4. Sea ice (ice loads and actions): Sea ice conditions are an important design criterion because they can impose significant loads on an Arctic coastal protection measure. Important design considerations for coastal protection measures are sea ice accumulation on the surface of the structures, sea ice motions, water level and sea ice cover fluctuations, and thermal expansions of the sea ice cover.
5. Sub-sea permafrost (see Part III, Ch. "Engineering challenges and considerations related to sub-sea perma-frost").

Protection measures and design

Commonly employed solutions for coastal protection are classified with respect to their impact on the natural and physical systems, human response, geometry, and materials as shown in Table 2–Table 3. These tables provide an initial overview of the protection measures examined in later sections and present a guide for analysis and mutual comparison. The focus in the following presentation is on protection measures impacting the natural and physical systems. The impact of protection measures on human response are not explicitly examined in this study. The coastal protection solutions in Table 2–Table 3 can be further divided into structural and non-structural measures. Common structural coastal protection measures include seawalls, bulkheads, revetments, groins, breakwaters, and protective beaches. Common non-structural coastal protection measures include vegetation, coastal drainage improvements, and coastal slope reshaping.

Table 2. Alternatives for Arctic coastal protection, adapted from [113]

Impact				**Changes to the natural, physical system**				
Function, problem		**Armoring structures, beach stabilization, backshore protection**		**Beach stabilization, harbor protection**		**Beach stabilization**		
Type	Seawall	Bulkhead	Revetment	Breakwaters	Groins	Vegetation	Groundwater drainage	Coastal slope reshaping
Geometry	Vertical smooth Stepped Curved Rubble mound	Crib Stepped Cantilevered Tie-back	Sloped	Headland Floating Detached Single System Submerged	Normal Angled Single Group Permeable	Shores not directly exposed to saltwater	Surface drain Bluff dewatering Internal drainage	Reduction of slope angle
Materials	Concrete Rock Steel sheet piles	Sheet-pile: steel, concrete, timber, aluminum. Gabions	Concrete Rock Geotextiles Gabions	Rock Steel Gabion Precast concrete Geotextile tubes Sheet-pile; steel, concrete, timber		Drains Perforated pipes Catchment basins Drainage blankets		

Table 3. Alternatives for Arctic coastal protection, adapted from [114]

Impact	**Changes to the natural, physical system**	**Changes to human response**			**Changes in both**		**No changes**
Function, problem	**Beach restoration**	**Adaptation and accommodation**			**Combinations**		**Do nothing**
Type	Protective beaches	Flood proofing	Zoning	Retreat	Structural and restoration	Structural, restoration, and adaptation	
Geometry	Dune, Dynamically stable beaches, Beach profile, Underwater berms	Elevated structures Raise grade Sandbags Flow diversion	Setbacks Land use restrictions Public lands	Individuals Communities Infrastructure Move structures	Any combination of 1, 2, or 3 alternatives	Any combination of all three alternatives except retreat	Let nature take its course
Materials	Borrow sites Dredged material Artificially made materials	Single family homes on timber piles	Drains, Perforated pipes Catchment basins, Drainage blankets				

Structural erosion protection measures

Structural protection measures are: (i) sea wall, (ii) bulkheads, (iii) revetments, (iv) groins, (v) breakwaters, and (iv) protective beaches. The following is a list summarizing key points of structural protective measures.

1. Seawall

A seawall is a structural protection measure built parallel to the shore to protect from erosion by waves and currents. Seawalls are commonly built on coasts that extend relative to the adjacent coasts with limited or no protective beaches as gravity structures. Seawalls are constructed as cast-in-place concrete with smooth, stepped or curved face, or as a rubble mound. The application of seawalls is limited to the land immediately behind, with adjacent areas often experiencing increased erosion rates. The advantages of seawalls include good erosion protection from moderate to high wave heights on cohesive and non-cohesive shores, low vulnerability to ice loads, and provision of direct boat access to the shore. Some of the weaknesses of seawalls include requirements for toe protection, foundations and anchoring, increased erosion in adjacent areas, relatively high initial and long-term costs, frost action in the backfill, and limited access to the beach.

2. Bulkheads

A bulkhead is a structural erosion protection measure built parallel to the shore that stabilizes the soil behind. Bulkheads are constructed of lighter materials than seawalls as their secondary function is to protect the shore from wave action. Bulkheads are constructed from sheet-pile elements, cast-in-place concrete, precast concrete, treated timber, and gabions. Similar as seawalls, their application is limited to the land immediately behind, with the adjacent areas often experiencing increased erosion rates. The advantages of bulkheads are good protection for low to moderate wave heights on cohesive and non-cohesive shores, provision of direct boat access to the shore, easy repair and low to modest construction skills. Some of the weaknesses include requirements toe protection and pile driving, frost action in the backfill, relatively high initial and long-term costs, vulnerability to sea ice and corrosion (especially gabions), increased erosion in adjacent areas, and limited access to the beach.

3. Revetments

A revetment is a structural erosion protection measure built at the toe of a bluff or at the front of a beach. A revetment usually is designed to follow the slope of the beach and it consists of an armour layer, a filter layer, and toe protection. Depending on the type of material in the armour layers, revetments are categorized as rigid or flexible. Rigid revetments are constructed with a cast-in-place concrete armor, while flexible revetments have an armor constructed with large rocks, prefabricated concrete blocks, sang bags or gabions. Some of the advantages of revetments are beach stabilization, backshore protection to moderate wave heights in cohesive and non-cohesive soils, reasonable costs in case of locally available materials, modest construction skills, absorbing settlements, low vulnerability to sea ice of concrete mats. Some of the weaknesses include restrained beach development, frost action in the backfill, vulnerability to sea ice and corrosion of gabion-based revetments, wave runup and progressive failure on concrete mats, sun and sea ice degradation of sandbags used for constructing revetments.

4. Groins

Groins are a structural erosion protection measure built perpendicular or at an angle to a non-cohesive shore to stabilize the beach by impeding the erosion rate. Groins are usually built in groups to form a groin field. They are usually constructed with timber, steel, concrete, gabions or as a rubble mound. The length and spacing of groins should be optimized with respect to the erosion processes at the site. The advantages of groins include build-up of beaches, beach access, modest construction skills and easy repair. Some of the weaknesses include increased down-drift erosion, regular maintenance, vulnerability to sea ice of gabions and sand tubes, vulnerability to corrosion of metal components, and local scour at the toes of structures.

5. Breakwaters

A breakwater is built offshore or connected to a shore such that it extends to the water to protect the coast from erosion by reducing the wave action on the coast. Breakwaters can be built on cohesive and non-cohesive shores in a group or single, bottom anchored or floating, and parallel or at a certain angle to the coast. Breakwaters are commonly constructed from cellular steel, gabions, concrete caissons, or as rubble mounds. The advantages of breakwaters include unrestricted access from the beach, sheltered mooring area, beneficial effects that extend over long shoreline sections, and no flanking. Some of the weaknesses of breakwaters include high construction and maintenance costs, vulnerability to moving ice, foundation failures, toe scour on the water-ward side, increased erosion on the down-drift side, navigation hazard, corrosion of steel and gabion breakwaters, and sea ice damage on gabions.

6. Protective beaches

Material that is eroded on non-cohesive beaches moves down-drift and nourishes a beach, or offshore where it can be deposited in an underwater bar. Material accumulated on such beaches or underwater bars contributes to erosion protection as a significant amount of wave energy can be dissipated over such beaches or underwater bars. A protective beach refers to a beach that is naturally maintained or created and nourished as an erosion protection measure. Beach nourishment should match natural material coarseness found at the beach or involve the placement if gravel or rock significantly larger than the natural material, which is known as dynamically stable beaches. The advantages of protective beaches include more beach shoreline, unrestricted access, protection over long stretches, and low vulnerability to ice damage. Some of the disadvantages include continuous or periodic maintenance with and associated expenses and need in specialized equipment.

Several design codes can provide useful references for the design of structural erosion protection measures. Some of these codes are: European Norms, design standards of the International Organization for Standardization (ISO), design standards of Det Norske Veritas and Germanischer Lloyd (DNVGL), the National Building Code of Canada (NBCC), and the International Building Code (IBC). In addition to the design standards, useful design references can be found in recommended practices published by ISO, DNVGL, American Petroleum Institute (API), Russian standards (SP), United States of America Corps of Army Engineers (USACE), several useful design manuals and workshop proceedings from Alaska.

Non-structural erosion protection measures

Structural protection measures are: (i) managements based on determinations of coastal hazard areas, (ii) vegetation, (iii) coastal drainage improvement, and (iv) coastal slope reshaping. The following is a list summarizing key points of non-structural protective measures.

1. Managements based on determinations of coastal hazard areas

Spatial planning of infrastructure should be based on maps with forecast of erosion, flood maps and zones. Spatial planning of infrastructure with respect to coastal hazards is an efficient mechanism in reducing negative effects on the potentially affected infrastructure and population. Hazards maps are developed with respect to certain recurrence intervals of the hazards such as a 1% chance of annual flooding or 100-year flood. The recurrence interval is a probabilistic estimate of frequency as a likelihood of an event of certain magnitude occurring within a given period. Historical events and simulations can be used to estimate recurrence intervals. Hazard maps are an important tool for decision makers to account for the potentially negative effects of hazards on infrastructure and population in the early design stages and evaluate vulnerability of communities and infrastructures in hazards prone zones.

2. Vegetation

Vegetation is a non-structural erosion protection measure applicable for sheltered shores. The application of vegetation as an erosion protection measure is hindered by short growth seasons of vegetation in the Arctic.

3. Coastal drainage improvement

Coastal drainage measure can be implemented on coastal slopes to improve its stability by reducing the groundwater level rise through surface drainage or drainage with perforated pipes, bluff dewatering, and drainage blankets.

4. Coastal slope reshaping

Coastal slope reshaping is implemented to increase the stability of a coastal slope. Slope reshaping is usually followed by planting vegetation or construction of bulkheads as it does not protect the slope from exposure to waves. Some of the advantages of non-structural erosion protection measures include relatively low cost, increased coastal slope stability, unrestricted and improved access to the beach. Some of the disadvantages include lack of direct protection from waves, short vegetation growth seasons in the Arctic, and reduced amount of usable land in the case of coastal slope reshaping.

Several design codes can provide useful references for the design of non-structural erosion protection measures. Some of these codes are: European Norms, NBCC, and IBC. In addition to the design standards, useful design references can be found in recommended practices published by ISO, DNVGL, API, and USACE.

Coastal risk assessment

The selection of a coastal protection measure should be an element of coastal risk assessment at the site of the planned protection measure. The process of risk assessment commonly includes two phases: risk analysis and risk mitigation. The risk analysis phase characterizes the hazards imposed by different threats (e.g., storms) at the site of the planned coastal protection measure and evaluates the potential consequences on the society and the environment (e.g., financial loss). The evaluation of consequences is a complex task that relies on qualitative and quantitative estimates of vulnerability (e.g., low damage, complete failure) at the site of the planned coastal protection measure with respect to different threats. Once a risk analysis is performed, different measures can be implemented to mitigate risks. The goal of the risk mitigation phase is to maintain risks at acceptable levels by applying a set of measures that reduce hazards at the site the planned measure (e.g., wave height reduction with a breakwater) and/or the vulnerability of the society or the environment (e.g., coastal retreat).

Managing the effects of climate change on coastal structure

In the coastal zone, the effects of climate change are likely to lead to higher erosion rates, increased thaw settlements, melting and erosion of ice wedges due to the changes in the active layer and the permafrost. Erosion rates might increase due to sea level rise and alterations in sea-ice dynamics with warmer seas and longer periods of open sea with reduced sea-ice coverage. Additionally, degradation of the permafrost and increasing active layer depth are likely to contribute to faster erosion rates due to a reduced capacity of coastal slopes to withstand erosion processes (e.g., thermoabrasion).

Sea level rise combined with changing storm dynamics (e.g., increased extreme weather and storm surge frequency) might increase the likelihood of coastal flooding and increase vulnerability of existing coastal infrastructure. A larger number of freeze-thaw cycles may contribute to faster degradation of materials (e.g., concrete) with higher chance of thaw-induced settlements and damage in structural elements (e.g., anchors) of coastal protection structures. Additionally, coastal protection structures may be affected by reduced bearing capacity in their foundations due to increase in active layer depth and degradation of permafrost. Increasing temperatures may lead to lateral deformations and settlements in coastal protection structures that affect their capacity of satisfying the serviceability limits, which may cause significant damage to the structural elements and nearby infrastructure. It is important to note that the existing technical solutions are often considered as valid options in managing the effects of climate change on coastal infrastructure.

Solutions and considerations for pipeline design

Onshore section

The design of onshore pipelines is commonly examined with respect to the following design considerations.

1. Thaw settlements

Thaw settlements occur in soils with high ice content where soil grains settle after ice has melted. Thaw induced settlements are an important design criterion as they can induce significant strains on a pipeline. The effects of thaw settlements on pipelines depend on the ice content in soil, and the shape and length of the soil thawing zone. The effects of thaw settlements are most severe at the transitions between thaw settling and thaw stable zones, where the highest strains occur due significant differential settlements. Mitigation measures include excavation of ice rich soils beneath the pipeline base to place the pipeline at deeper depth or to replace the excavated soil with thaw stable material. Another mitigation measure is to increase pipeline thickness or pipeline strength until induced strains do not cause damage in the pipeline. Installing a cooling system to reduce the heat flux from the pipeline or adding surface insulation are additional mitigation measures that can inhibit the development of the thawing zone. Another common mitigation measure is to elevate pipeline on aboveground support, such as thermopiles.

2. Frost heave

Frost heave occurs mainly because of formation of ice lenses between the soil particles during the freezing process. Frost heave is commonly exhibited as surface expansion if the soil is free to move. In case of restricted movements, frost heave can induce significant forces on infrastructure. Frost heave can occur around pipelines that operate at mean annual temperatures below zero. Such conditions can be often encountered around gas pipelines due to the Joule Thomson effect, which relates reduction of gas temperature due to expansion. The occurrence of frost heave depends on freezing temperatures in soil, a source of water to migrate to the freezing front, and soil that permits free water to migrate through the soil. Effects will vary along the pipeline due to natural changes in ground conditions. Special attention should be given to pipeline transitions between frost stable (e.g., sand) and frost susceptible soils (e.g., silt), slope crossings, downslope sections of pipelines, and sections with ice segregations as such areas may induce high heave forces on pipelines. Mitigation relates to countering one of the necessary conditions for the occurrence of frost heave, such as increasing pipeline insulation to limit the development of the frost bulb, drainage to reduce the supply of water to the freezing front, increasing the operating temperature of the pipeline, or increasing the thickness or strength of the pipeline material.

3. Slope instability due to soil thawing

A slope might be stable in frozen and unfrozen conditions but may fail during the thawing process. The presence of a pipeline can destabilize a slope in the case that the pipeline operates at the mean annual temperature above freezing. Warm temperatures in a pipeline can expand the thawing zone, which can lead to the generation of excess pore pressures that may destabilize the slope. A common mitigation measure for slope instability due to soil thawing is to install surface insulation that aims to reduce generation of excessive of pore pressure.

4. Upheaval buckling

Upheaval buckling occurs in longitudinally constrained pipelines due to compressive forces that result from the tendency of pipelines to expand due to higher temperatures and pressures than the ones during the installation. Upheaval buckling is commonly initiated on an overbend (i.e., vertical curve) where the weight of the pipeline and the soil above are not enough to maintain the pipe in place. Upheaval buckling is often mitigated by planning for enough backfill, which is estimated by an upheaval buckling analysis.

5. Buoyancy of pipelines in thawing permafrost

Soil thawing can result in a rapid generation of excess pore pressures that induce significant buoyant forces on a pipeline. A pipeline may float to the surface in such conditions if the buoyant forces exceed the forces holding the pipeline in position. Some of the common mitigation solutions are additional weights, increased backfill, pipeline rerouting, or anchoring.

Shore transition

The design of shoreline transitions will be examined with respect to the following design considerations: shoreline erosion, ice ride up and pile up, routing and massive ice, thaw settlements, and frost heave. Previous discussions on thaw settlements and frost heave apply here.

1. Shoreline erosion

Shoreline erosion resulting from hydrological and thermal processes on Arctic coasts is an important design element of shoreline pipeline transitions. Erosion of the backfill of a pipeline may reduce the its stability and increase its exposure to environmental conditions (e.g., ice actions), which may negatively affect the pipeline safety. Shoreline erosion is estimated with respect to the design lifetime of the pipeline based on long term erosion rates. Unless an erosion protection structure is planned, long term estimates of the shoreline erosion are important to determine the setback distance from the shore to the location where the pipeline surfaces, also known as the pipeline daylight location. The setback distance also includes the estimates of the ice ride-up and pile-up. The design of erosion protection structures is dependent on site specific conditions including design water level, design wave, structure height and wave run up, sea ice conditions, construction materials, frost heave, thaw settlements, flanking protection, ground conditions, filtration and drainage, toe protection, and human and environmental concerns. Some of the shoreline erosion protection solutions include tunnels, sheet pile walls, cellular sheet pile, and concrete seawalls.

2. Ice ride-up and pile-up

Ice ride-up and pile-up occur at shores primarily during the later fall/early winter freeze up or during the spring break up. Ice pile-up is associated with a large accumulation of floating ice sheets that are pushed up the shore in random ordering. Ice ride-up occurs similarly as ice pile up, with the difference that the floating ice sheets remain approximately flat as they slide onshore. Ice riding up and piling up the shore can lead to damages in above ground sections of pipelines and pipeline support infrastructure. A common approach to mitigate damage from ice ride-up or pile-up is to move away the exposed sections of pipelines and supporting infrastructure from the shoreline. This means that the total set back distance should include the estimate shoreline erosion during the lifetime of a pipeline and the estimated ice ride-up and pile-up distance.

3. Routing and massive ice

Cyclic freezing and thawing of soil over many years can lead to the formulation of massive ice wedges. Intersections of ice wedges with the shoreline can result in the formation of gullies that can affect the stability of pipelines. Detailed investigations should be conducted in situations where the position of ice wedges on the shoreline cannot be accurately determined to avoid erosion due to gullying effects.

Offshore section

The design of offshore pipelines shall be examined with respect to ice gouging, strudel scour, grounding, pounding and wallowing of ice, liquefaction, thaw settlements, frost heave, and upheaval buckling. The discussions on thaw settlements, frost heave and upheaval buckling in previous sections apply here.

1. Ice gouging

Over time sea ice sheets tend to pile up and create ridges such that the keels of these pressure ridges can enter shallow water depths and gouge the seafloor. Ica gouging is an important design criterion for offshore pipelines as an ice keel induces lateral and vertical stresses than can damage a pipeline. Damage potential on a pipeline due to ice gouging depends on the properties of the pipeline, soil characteristics, depth of the pipeline, and the soil displacements. Ice gouging is often mitigated by ensuring sufficient burial depth, estimated based on seabed scans. A pipeline should be buried sufficiently such that the maximum estimated ice gouging does not induce strains in the pipeline that exceed the pipeline design levels.

2. Strudel scour

Strudel scour can occur in areas where an onshore river encounters bottom fast ice sheets. In such situations, the river water can overflow the bottom fast ice sheets in the nearshore zone and drain through ice cracks. The flow rates through the ice cracks can be relatively high and induce scour on the seabed, known as strudel scour. Strudel scour can expose pipelines and subject them to high hydrodynamic loads. Strudel scour is often mitigated by increasing the burial depth of pipelines.

3. Grounding, pounding and wallowing of ice

In certain conditions, the pressure ridges created by the pile-up of sea ice sheets can be driven onshore and grounded. If grounded over a pipeline, they can provide additional loading and potentially damage the pipeline. Similar situation can occur if an accumulation of sea ice rubble known as stamukha forms over a pipeline. Backfill above the pipeline should be sufficiently thick to prevent the development of excessive strains in the pipeline due to additional loading from ice grounding. Dynamic loading on the seabed in the form of ice pounding can occur when ice bounces on the seabed in response to wave loading. Such loading can lead to accumulation of excess pore pressures in the soil around a pipeline and the loss of stability of the pipeline. Ice pounding can be mitigated with increased backfill. Ice wallowing occurs due to local erosion around grounded ice due to actions of sea currents waves and it can be mitigated with increased backfill.

4. Liquefaction

Waves induce fluctuations of water pressure at the surface of a porous seabed, which induce excess pore pressure and effective stress variations in the seabed. The excess pore pressures can gradually increase over time due to cyclic water pressure variations at the seabed surface. In the case that the excess pore pressures exceed the mean effective soil stress, the soil reaches the liquefaction failure state. Wave induced liquefaction is unlikely to occur on soils that were subjected to long term histories of wave loading. However, wave induced liquefaction can occur in loosened soil (e.g., backfill material), when there is slow sedimentation, and when the seabed is active (i.e., soil being constantly reworked). In the context of pipeline design, liquefaction of soil in the proximity of a pipeline can lead to the pipeline floatation, which may lead to increased strains in the pipeline. The hazard of pipeline floatation due to liquefaction can be mitigated by increasing the burial depth, adding more coarse-grained cover, and by increasing the weight of the pipeline.

Construction techniques for landfalls

1. Temperate climate

The typical landfall construction techniques for subsea cables and pipelines in temperate regions are Open Cut Trenching (OCT) and tunnelling and Horizontal Directional Drilling (HDD). The choice of one or the other technique depends on the geological, morphological, environmental, cost and geotechnical conditions of the sites. A conventional OCT consists in trenching of the beach and burying of the pipe relatively deep with the trench backfilled after the pipeline installation. The goal is to reduce as much as possible the vulnerability of the pipeline to the coastal processes. Depending on the site conditions, the construction of a cofferdam is required if the trench is unable to remain open during the pipe laying operations.

2. Arctic climate

In the Arctic, the main method for landfall construction is OCT. However, tunnelling and horizontal drilling may also be feasible. The main difference in landfall planning in the Arctic compared to temperate region resides in the fact that the onshore section of the pipeline in Arctic areas is generally situated above the ground surface to avoid thaw instabilities. The fact that pipelines need to lay above the ground surface in permafrost areas results in the necessity of having a transition between below- and above-surface section of the flowline in the landfall area. The exact location of this transition zone is called the daylight location. The daylight location should be situated at a safe distance from the shore, usually defined as the sum of the estimated long-term coastal erosion (considering the lifetime of the structure) and of the ice encroachment distance.

Relevant design codes and recommended practices

Several design codes provide information for pipeline design. Some of these codes are: European Norms (ENs), ISO, DNVGL, NBCC, IBC, and SP. In addition to the design standards, useful design references can be found in recommended practices published by ISO, DNVGL, API, and USACE.

Considerations for accounting of climate change in pipeline design

In case of warm pipelines supported by piles, increased air and soil temperatures are likely to reduce their bearing capacity due to a decrease in adfreeze strength between the pile and the frozen soil. Increased active layer depth will reduce the effective embedment length of the piles in the frozen soil zone. The use of refrigerated or thermo-piles to counter these effects is likely to be limited as the increased air temperatures reduce the cooling capacity of such systems. In case of warm pipelines, these problems may be reduced by decreasing the operating temperature of pipelines. However, this would also increase the pumping cost and susceptibility to wax formation in the pipeline. In case of chilled gas pipelines, increasing ground temperatures will expand the zone of discontinuous permafrost northwards. Expanding discontinuous permafrost will increase the number of transitions between thaw stable and unstable zones, which may lead to significant frost heave forces on the pipeline. In such situations, the negative effects of climate change can be reduced by adapting the operating temperature to local conditions and keeping it slightly below freezing.

Most of the effects of climate change detected in the onshore zone extend to the shore transition and the offshore zones. In the shore transition zone, pipelines may be exposed to higher erosion rates, increased thaw settlements, melting and erosion of ice wedges due to the changes in the active layer and the permafrost. Erosion rates might increase due to sea level rise and alterations in sea-ice dynamics with warmer seas and longer periods of open sea with reduced sea ice coverage. Additionally, degradation of permafrost and increasing active layer depth are likely to contribute to increasing erosion rates due to reduced capacity of coastal slopes to withstand erosion processes (e.g., thermoabrasion). Sea level rise combined with changing storm dynamics (e.g., increased extreme weather frequency) might increase the likelihood of coastal flooding and increase vulnerability of existing coastal infrastructure. A larger number of freeze-thaw cycles may contribute to a faster degradation of materials (e.g., concrete) with higher chance of thaw-induced settlements and damage in structural elements (e.g., anchors) of coastal protection structures. Additionally, coastal protection structures in the transition zone may be affected by a reduced foundation bearing capacity due to an increase in the active layer depth and degradation of permafrost. Increasing temperatures may lead to lateral deformations and settlements in coastal protection structures that affect their capacity of satisfying the serviceability limits, which may cause significant damage to the structural elements and nearby infrastructure. Furthermore, climate-driven changes may lead to increased thaw settlements, reduced upheaval buckling capacity, and liquefaction in the off-shore zone.

Engineering challenges and considerations related to sub-sea permafrost

Sub-sea permafrost can be considered as a geohazard phenomenon which should be avoided. It is recommended that infrastructure design provides maintenance of the frozen state of sub-sea permafrost (as it was before the construction) during the whole life of a structure. This corresponds to the approach of "Maintain Existing Ground Thermal Regime" in the North American practice or the Principle 1 of the Russian methodology.

The following challenges related to sub-sea permafrost can be outlined (based on [115]):

1. Uneven thaw settlement and overstraining of warm oil pipelines, especially in the nearshore area.
2. Differential settlements and failure of foundations due to thawing of permafrost.
3. Problems with dredging operations due to encountering of ice-bounded material.
4. Difficulties with interpretations of seismic reflection records.
5. Submarine slide activities.
6. Difficulties associated with pile deployment (direct pile driving), and possible decrease of adfreeze strength due to distribution of saline water along the pile.

An engineer must be aware of several specific geo-cryological and other phenomena confined to sub-sea permafrost. Possibilities for locating structures in the areas of presence of such phenomena are limited or completely absent. In any case, these phenomena must be taken into considerations in design. These phenomena are:

1. Thawing of sub-sea permafrost (or thermokarst)
2. Sub-sea pingos of different origin
3. Taliks (open and closed)
4. Diverse submarine mass movements
5. Deposits of gas hydrates
6. Flow of free gas
7. Seasonal bottom ice in deltaic areas

Methods for investigation of sub-sea permafrost include probing, drilling, sampling, drill hole log analysis, temperature and salt measurements, geological and geophysical methods (primarily seismic and electrical), geological and geophysical models.

PART IV. THE MONITORING STAGE

Introduction to the MONITORING STAGE

The goals of monitoring are to provide an assessment of the stability and serviceability of the structure during its lifecycle, and to document environmental conditions during maintenance. The assessment shall be used as a tool for safe functioning of the infrastructure. In the present guidelines, monitoring is limited to needs due to interaction between ground, atmosphere and water with infrastructure located in the coastal zone. Monitoring needs such as internal integrity of buildings, stresses in pipelines, integrity of the pipelines, internal corrosion of pipelines, and vibrations effects on foundations from different sources are outside of the scope of these guidelines.

Monitoring of coastal infrastructure may utilise several practices, standards, and reviews of CAN/CSA, Eurocode 7, ISO, US Army Corp of Engineers, GOST and SP, Deltares.

Monitoring plan considerations

What and where to exactly monitor are essential considerations. In addition to other considerations given in this chapter, selecting parameters to be monitored and instrument location is dependent on the type of infrastructure and environment.

A set of "key variables" should be established for the monitoring plan. The following variables can be included in the monitoring plan considerations (more variables can be included):

1. Metocean data collection: wave climate, wind, ice movements (level ice, ice-pile up and ride-up (i.e. ice encroachment), ice features and their parameters (ice ridges, stamukhas, icebergs).
2. Surge flooding.
3. Coastal erosion in sensitive areas.
4. Mapping of river overflood.
5. Mapping of strudel scours.
6. Ground temperatures (onshore and offshore).
7. Presence of icebergs and ice ridges, and gouges caused by these phenomena.
8. Soil mass movements (onshore and offshore).
9. Bathymetry.
10. Specific hazard phenomena (as gas emission craters onshore, pingo-like features "diapiry" in offshore).
11. Coastal protection structures (integrity and particularities of material performance).
12. Deformations of the structures.
13. Land subsidence/uplift.
14. Loads on the structures.

Coastal infrastructures are designed to tolerate some level of deterioration before significant loss of functionality can be expected. Monitoring should therefore be aimed on how well a structure is functioning in addition to monitor the condition. Condition monitoring and performance/functionality monitoring have many monitoring plan considerations in common. The *CEM* [8] includes a good overview of monitoring plan considerations, being the main considerations the following:

1. Fiscal constraints. Realistic funding is important for effective monitoring.
2. Data considerations (data accuracy, quantity, quality, site specific conditions, requirements to instruments).
3. Frequency of condition monitoring is usually spread evenly over the service life of structures. Frequency of performance/functionality monitoring can be more varied throughout the service life of structures. Furthermore, sampling rate, sample length, sampling interval and measurement duration should be considered.
4. Instrument selection is a trade-off between quality, quantity and cost. There are several general considerations for instrument selection.

5. Other considerations are the health and safety of personnel who install, maintain, remove instruments, and retrieve data, environmental impact and interference of instruments with shipping navigation.

In addition to what is recommended in the *CEM* [8], the recommendation is to gather results of monitoring in one monitoring system. Considerations for the monitoring system are:

1. GIS-based.
2. Data collection should be carried out as much as possible in "human-free regime".
3. System should have a warning regime based on a threshold (as value or trends for the values) for the main monitoring parameters. Thresholds can be determined based on the data obtain at the prospect stage. An action plan can be elaborated based on the warning regime. The action plan may include reduced activity, evacuation or shut down of activities. The monitoring system should also utilize hydrometrological forecasts to anticipate on extreme weather events.
4. An optimal monitoring system should combine input from different monitoring techniques.
5. Results of evaluation of the main monitored parameters should be reported to the responsible body in a routine manner.
6. Safe data storage and transmission must be considered.

A different aspect of monitoring that should be considered is its sustainability. Economy, ecology and society aspects should be considered for the monitoring plan. Examples of how economy, ecology and society can be considered are given below:

1. Make sure equipment or parts of equipment cannot get worn down or destroyed by weather conditions or animal life. This can lead to environmental pollution or parts being eaten by the wildlife. Society will also benefit from not having stakeholders in a bad daylight, and economically by preventing maintenance and only having to install monitoring systems once.
2. It can be beneficial to involve the local society in monitoring. Educating locals to understand the device which is installed in their vicinity is an advantage. Another advantage may come from employing locals to do manual work related to maintenance or the monitoring itself. Employing locals is beneficial from social, economic and environmental points of view. Traveling costs and emission will be reduced compared to the travels of non-local employees.
3. Power supply is an environmental consideration. Remote systems which cannot be connected to electricity net can be driven by battery or generator, but solar panel- or wind energy driven systems might have a beneficial environmental effect. In addition, savings will be done on travelling costs for replacement of batteries or refuelling.
4. Another environmental and economical consideration is to have a remote data transfer system, which reduces the need for traveling and thereby costs and emissions.

Monitoring methods

This chapter summarises common available monitoring methods for coastal infrastructure. The scope of this chapter is to present methods possible to be used to monitor external factors influencing coastal infrastructure. External factors are influences by changes or variations in the ground thermal and hydrological regimes, water regime or weather conditions which directly and indirectly influence the integrity of operating infrastructure. In these guidelines monitoring is divided in different fields and these are:

1. Visual inspection
2. Deformations
3. Ground temperatures
4. Geomorphology
5. Hydrology
6. Meteorology
7. Vegetation cover
8. Repeated investigation of geotechnical properties of the ground

9. Methods providing artificial cooling of the ground

Visual inspection

Visual inspection should be organized on:

1. Repeated basis
2. After severe environmental events (as flooding, hurricanes, severe rainfalls, events of ice encroachment
3. After serious accidents of technological nature (collisions of boats with piers, overload of the port facilities by the dead weight of the goods and machines, fire, significant leakages of hot and cold water and other fluids, etc.)

Monitoring by visual observations and photographical documentations can involve:

1. Cracks in concrete/brick walls
2. Deflections on structures
3. Conditions of surfaces made of concrete, i.e. surface of walls and foundation above the ground
4. Uniform and local corrosion hot spots in steel piles and sheet pile walls
5. Displacement or erosion of breakwater stones and sandbags
6. Conditions of geotextiles and sandbags
7. Abrasion of concrete by ice rubbing and impact
8. Accumulation or erosion of sediments in the vicinity of structures
9. Changes in vegetation over seasons
10. Ground settlements due to thawing of ground ice in permafrost
11. Accumulation of snow (that can affect ground temperatures when blocking convection under elevated buildings on piles, when accumulated along the road pavements)

Deformations

Deformations of infrastructure can lead to internal structural damage and risks to the environment. The goal of monitoring is to detect deformations and the rate of deformation to reveal if deformations exceed the allowed limits. Deformation monitoring is also an input for the decision to take measures. Deformation of infrastructure can be directly detected by monitoring systems installed on constructions and indirectly by geomatical and geodetical surveying methods. In addition, monitoring of deformations and stresses in soil bodies under or adjacent to constructions provides insights into the ground conditions during construction and operation phase. For Arctic infrastructure located on permafrost, monitoring ground temperatures is essential for preventing deformations.

Geomatical and geodetical surveying methods are:

1. Levelling
2. Surveying with total station
3. Surveying with global navigation satellite systems
4. Hydrostatic levelling
5. Differential SAR interferometry
6. Laser scanning

Tools which can be installed on buildings or in ground bodies for deformation monitoring are:

1. Extensometers
2. Inclinometers
3. Settlement plates
4. Tilt meters
5. Strain gauges
6. Fiber optic sensing
7. Pressure cells
8. Piezometers

The time interval and specific locations of deformation monitoring depends on the geotechnical and geothermal setting, construction phase, and type of infrastructure. Deformation monitoring should start before ground conditions are influenced by construction. Infrastructure founded in or on stable ground conditions requires less monitoring than infrastructure founded on settlement or heave prone ground conditions (for example silts and ice-rich permafrost ground). The extent of monitoring depends on the type of structure and its thresholds for deformations. More frequent monitoring shall be considered for the first few years after construction is completed. Afterwards, a better understanding of the magnitude of deformation can lead to the decision to change (reduce or increase) the monitoring frequency.

Ground temperatures

The bearing capacity of frozen ground is much higher than thawed ground. It is important that the observed ground temperatures correspond to the values used in design. Knowledge of ground temperatures gives the opportunity to anticipate settlements, which is the reason why temperature changes in the ground are monitored. The ground surface temperature (GST) is an important parameter to understand the thermal conditions and evolution of ground temperatures. Artificial cooling systems which control the heat flux from building to ground, should always be monitored.

Changes in the ground temperature regime can occur due to weather and climate changes, but they can be also induced by infrastructures. The first measurements of ground temperatures start as a part of the geocryological survey before constructions, in order to define the initial site conditions. It is reasonable to continue these measurements throughout the construction and operational phases. For these first measurements it can be suggested to arrange them within and outside (in an area which will not be affected, or less affected) the construction place. Such setup will help differentiating between natural temperature variations and induced temperature variations. Multiple temperature reference points should be established in permafrost in order to obtain a representable temperature reference.

Special considerations must be used to monitor permafrost temperatures in the proximity of large water bodies. Large water bodies can have strong effect on local permafrost regime. For instance, permafrost normally have a thermal gradient close to the shoreline. Planning of boreholes location for thermal monitoring in such cases should follow existing recommendations and may be based on earlier measurements of ground temperatures in the area and may also utilize results of numerical modelling. A denser network of boreholes for thermal modelling can be recommended for shoreline and river crossings of pipelines in permafrost-affected coastlines/riverbanks. In these cases, ground temperatures could be monitored in directions along and across a pipeline. Technical recommendations for monitoring of ground temperatures in permafrost are presented in the TG.

Geomorphology

Changing geomorphology (topography and bathymetry) in the vicinity of structures can result in negative operational consequences. The goal of geomorphology monitoring is to detect critical changes in geomorphology which can influence infrastructure. The erosion of ground bodies or deposition of sediments may lead to changes in the bearing capacity of the ground carrying the structure, induce lateral forces on structures, change flow paths of rivers creating unforeseen new waterways. A change in flow path in coastal areas can change wave induced forces on coastal structures and also change the geometry of structures as, for example, artificial islands, dams and embankments. Repeated measurements can help monitoring changes in geomorphology which can affect structures.

Monitoring methods for geomorphic changes in the coastal zone can be summarized as following:

1. Repeated mapping of ground or coastal seabed level for construction of digital elevation models. Common topographic survey methods are performed by use of levelling, surveying with total station, real-time kinematic GPS and differential GPS

measurements. Mapping can be utilized with aerial and satellite surveys, including surveys with UAVs. These techniques can be executed in the tidal zone at low water or by wading in shallow water depths.

2. Repeated measurements of distance between a fixed, stable reference point inland and the coastal bluff (spot measurement). Use of simple measuring tapes or total station mapping are suitable methods. The position of coastal bluffs can also be measured directly with a real-time kinematic GPS and differential GPS measurements.
3. Time lapse cameras are useful instruments for observation of coastal processes, which can be used for quantitative assessment.
4. Remote sensing techniques as InSAR, LiDAR and structure for motion are common. Airborne LiDAR is also available for bathymetry mapping in shallow waters.
5. Single beam echo sounding, side scan sonar and multibeam echo sounder are techniques to map the bathymetry of waterbodies.

Monitoring of bathymetry in harbours, approach channels and along pipelines should be done in spring after sea ice has retreated or after river break up. Most of the yearly river discharge and sediment transport happens within a couple weeks after river ice break up. Changes in river and river outlets will be concentrated during this period. Changes in bathymetry along pipelines shore crossings should be monitored after sea ice has retreated. Retreating coastlines with infrastructure on the coastal plain should be monitored at least once a year. Depending on the rate of retreat and importance of the infrastructure, monitoring of retreating coastal crests can be increased or decreased. It is recommended to perform surveys after severe storm events. Topographic monitoring of rock and soil slopes can be done continuously or daily in settings where slope failure could endanger infrastructure (in such situation inhabitants are normally already evacuated). Monitoring should be especially performed during and after heavy rains.

Hydrology

The goal of hydrology monitoring is to gather information about hydrological conditions that can influence infrastructure. Relevant parameters that should be monitored are:

1. Water level in water bodies
2. Wave climate
3. Currents
4. Sea water temperature
5. Sediment transport (both bedload and suspended load)
6. River discharge and velocity
7. Groundwater parameters (table and pressure, flow, temperature, quality)
8. Water content in slopes and earth dams
9. Timing of the sea and riverine ice breakup
10. Ice parameters (concentration, thickness and other physical parameters (temperature, salinity), mechanical properties)
11. Ice forces on infrastructure
12. Snow (timing for snow cover, snow thickness, wetness, other required parameters)
13. Avalanche activity (routine surveys for assessment of avalanche hazard, avalanche events and their parameters)

Monitoring river discharge, its sediment transport and flow velocity are relevant mostly in the melting season when most changes and high discharge can be expected. Depending on the technique, the monitoring frequency can vary between continuously or at a regular interval. River ice break-up should be monitored closely in spring.

Oceanic wave and current climate are continuously monitored by national services. If needed, wave climate can be monitored at the site.

Groundwater pressure in natural slopes should be monitored if a possible failure of the slope can damage infrastructure. Groundwater pressure should be closely monitored especially after heavy rainfall events or in the melting season. Groundwater pressure close to infrastructure should be closely monitored during construction.

Meteorology

Monitoring weather comprises the monitoring of air temperature, wind speed, wind direction, humidity, precipitation, atmospheric pressure, visibility and cloud ceiling. Monitoring can be done on land, at sea, and from planes and satellites. Weather monitoring should be done continuously. Depending on the importance and location of infrastructure a local weather station can be installed on the site.

Vegetation cover

It can be suggested to monitor the state of vegetation cover in the areas around infrastructure. Changes in vegetation cover, especially its deprivation, may lead to (i) activation of aeolian sediment transport in coastal areas, which will cause topographical changes, and (ii) changes in thermal regime of permafrost. The goal of vegetation cover monitoring is to detect vegetation changes on permafrost ground in the vicinity of infrastructure. One may suggest monitoring vegetation cover every 1–2 years. The following methods can be used to monitor vegetation:

1. Field observations
2. Remote sensing of greenness rate of change
3. Use of spectroradiometer, SAR
4. Repeated aerial photography

Repeated investigations of geotechnical properties of the ground

Reinvestigations of geotechnical properties of the ground can be considered if (i) one could expect that the ground properties change significantly during the construction, (ii) if the replacement of the ground took place, (iii) artificial ground was placed on the natural ground, or (iv) due to other considerations (for instance when difficult and unexpected ground conditions were encountered during the construction).

Methods providing artificial cooling of the ground

Passive and active solutions for artificial cooling may be utilized. The performance of systems providing artificial cooling shall be supervised via monitoring of ground temperatures and the elements of the systems themselves.

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Development of coastal infrastructure in cold climate
Summary Guideline

SFI SAMCoT REPORT

This report is a Summary Guideline for development of coastal infrastructure in cold climate and is prepared within the SFI Sustainable Arctic Marine and Coastal Technology (SAMCoT).

The Summary Guideline follows the structure of a more comprehensive Technical Guideline established within the SFI, both aiming to give guidelines needed by the industry for the design of environmentally friendly and sustainable coastal structures and technology in cold regions. Recommendations are provided where appropriate and possible following the Prospect stage, the Design stage and the Monitoring stage.

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