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# Prevention and control measures for coastal erosion in northern high-latitude communities: a systematic review based on Alaskan case studies

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## Abstract

Erosion along high-latitude coasts has been accelerating in recent decades, resulting in land loss and infrastructure damage, threatening the wellbeing of local communities, and forcing undesired community relocations. This review paper evaluates the state of practice of current coastal stabilization measures across several coastal communities in northern high latitudes. After considering global practices and those in northern high latitude and arctic settings, this paper then explores new and potential coastal stabilization measures to address erosion specific to northern high-latitude coastlines. The challenges in constructing the current erosion control measures and the cost of the measures over the last four decades in northern high-latitude regions are presented through case histories. The synthesis shows that among the current erosion controls being used at high latitudes, revetments built with rocks have the least reported failures and are the most common measures applied along northern high-latitude coastlines including permafrost coasts, while riprap is the most common material used. For seawalls, bulkheads, and groin systems, reported failures are common and mostly associated with displacement, deflection, settlement, vandalism, and material ruptures. Revetments have been successfully implemented at sites with a wide range of mean annual erosion rates (0.3–2.4 m/year) and episodic erosion (6.0–22.9 m) due to the low costs and easy construction, inspection, and decommissioning. No successful case history has been reported for the non-engineered expedient measures that are constructed in the event of an emergency, except for the expedient vegetation measure using root-wads and willows. Soft erosion prevention measures, which include both beach nourishment and dynamically stable beaches, have been considered in this review. The effectiveness of beach nourishment in Utqiagvik, Alaska, which is affected by permafrost, is inconclusive. Dynamically stable beaches are effective in preventing erosion, and observations show that they experience only minor damages after single storm events. The analysis also shows that more measures have been constructed on a spit (relative to bluffs, islands, barrier islands, and river mouths), which is a landform where many Alaskan coastal communities reside. The emerging erosion control measures that can potentially be adapted to mitigate coastal erosion in high-latitude regions include geosynthetics, static bay beach concept, refrigerating techniques, and biogeochemical applications. However, this review shows that there is a lack of case studies that evaluated the performance of these new measures in high-latitude environments. This paper identifies research gaps so that these emerging measures can be upscaled for full-scale applications on permafrost coasts.

## 1. Introduction

High-latitude coastlines are influenced by several factors that set them apart from lower latitude coastlines including the presence of sea-ice and permafrost and are among the most dynamic in the world (Jones *et al* 2009a, Mars and Houseknecht 2007, Overeem *et al* 2011, Lantuit *et al* 2012, Farquharson *et al* 2018, Irrgang *et al* 2018, Novikova *et al* 2018). In some cases, high rates of coastal change can threaten coastal infrastructure and communities and create a need for erosion prevention. Solomon and Covill (1995) and Cunliffe *et al* (2019) noted that, rather than a slow steady process, erosion can occur in an episodic manner with short-term erosion rates that greatly exceed the long-term average rate. Accelerating rates of erosion at high-latitudes can be attributed to a longer open-water period or sea ice decline (Overeem *et al* 2011, Cai *et al* 2018, Farquharson *et al* 2018, Kwok 2018), shifting of shorefast ice to frazil ice (Aré *et al* 2008), shifting of multiyear ice to seasonal sea ice (Kwok 2018), sea surface temperature (Costard *et al* 2007, Overeem *et al* 2011), more frequent or severe storms (Manson and Solomon 2007), and the warming and thawing of permafrost (Nelson *et al* 2001, Romanovsky *et al* 2010, Rowland *et al* 2010, Grosse *et al* 2011, Sinitsyn *et al* 2020). More recently, Jones *et al* (2018) demonstrated a sustained increase in erosion over the last decade along the highly dynamic permafrost-affected Drew Point section of the Beaufort Sea coastline and the complexities associated with the factors most responsible for interannual variability in permafrost bluff erosion. Farquharson *et al* (2018) also demonstrated the complexities of coastal changes in permafrost regions by highlighting the high spatial variability of these changes across various types of coastal morphology and an increasingly dynamic permafrost coast of northwest Alaska. Lantuit and Pollard (2008) also reported such complexities after observing a decrease in mean annual rate of shoreline erosion on Herschel Island, which is also a permafrost-affected region, but an increase in erosion rate for segments of these shorelines with high ground ice content.

The economic impacts of climate change on Alaska's infrastructure and land losses associated with coastal erosion have been quantified under various climate forcing scenarios (Cole *et al* 1999, Larsen *et al* 2008, Melvin *et al* 2016). In general, studies indicate that projected climate change could impose additional costs due to infrastructure damage in Alaska and across the pan-Arctic (Hinkel *et al* 2003, Hjort *et al* 2018). Such climate-induced expenditures increase substantially as more comprehensive infrastructure inventories are considered. The uncertainties in climate projections (Friedlingstein *et al* 2014, Nordhaus 2018) may also increase the uncertainties in these predicted expenditures. A recent study by Melvin *et al* (2016) showed that cumulative costs

of climate-related damages to Alaskan infrastructure from year 2015 to 2099 were estimated to be \$5.5 billion for Representative Concentration Pathway (RCP) 8.5 (representing the highest greenhouse gas emissions scenario projected by the Intergovernmental Panel on Climate Change (IPCC)) and \$4.2 billion for RCP4.5 (representing stabilizing greenhouse gas emissions scenario).

Due to the severe impacts of coastal erosion on the lives and livelihood of northern indigenous communities and the high costs of implementing coastal protection, some villages have started to consider community-based relocation. The urgency and constraints of community-based relocations due to coastal erosion have been discussed in many studies (Shearer 2012, Marino 2012, Bronen and Chapin 2013, Gorokhovich *et al* 2013, Maldonado *et al* 2013, Bronen 2015). These studies generally agree that erosion, which has been considered a slow geomorphological process, should now be included under the statutory definition of disaster, and relocations should be community-led and government-supported so that the displacement efforts are in agreement with the culture and traditional values of local communities (Bronen *et al* 2019).

In some northern high-latitude populated regions with high coastal erosion rates, plans were established for community relocations and efforts are underway for the construction of erosion control structures (Radosavljevic *et al* 2016, Novikova *et al* 2018, Irrgang *et al* 2019). The efforts, however, are insufficient to address coastal erosion in high-latitude regions, especially those influenced by permafrost, and are currently of little help to local residents in adapting to and transitioning into a new coastal norm that is characterized by high erosion rates and a more dynamic coastal system. This is because the erosion prevention structures were designed based on their local historical trends, while the trends are dynamically changing and the structures can no longer be effective. Given the social context of the indigenous people and their long history of ties to the land and sea, community-based relocations are often complex and not feasible. Even when relocation is attempted, such as the case in Shishmaref, Alaska, which is affected by rapid barrier island migration and coastal erosion, the planning can last for more than 10 years and the relocation costs are projected to be at least about \$180 million (Marino 2012). Erosion prevention structures are still in need even in those plan-to-move communities to help reduce damages to current civil infrastructures while planning and implementation take place. Therefore, there exists an urgency of identifying potential adaptations for northern high-latitude coastal erosion and change. One method of identifying potential adaptations is through a systematic review on the prevention of coastal erosion in key northern high-latitude areas.

Coastal stabilization projects have been one of the most challenging types of construction faced by contractors globally due to the complexities of various environmental forcing factors such as storm impacts, sediment transport, and deposition patterns. Site specific risks, which are sometimes difficult to be distinguished from other factors, can lead to catastrophic failures of the coastal protection structure in question. Errors in field investigations, design, construction, and maintenance can also reduce the effectiveness of the measures. In addition, extremes of climate and weather, which are changing from historical values (Ayyub 2018), introduce more uncertainties to coastal engineering practice at local levels. Such projects, when located at northern high latitudes, are further complicated by the presence of sea ice, changes in sea ice extent, the harsh frigid environment, permafrost thaw, and thermokarst. Across the highly scattered scientific publications and gray literature, opinions and evidence regarding the effectiveness of long- and short-term high-latitude coastal erosion control vary greatly. While some studies (e.g. Ogorodov 2003, Carter and Smith 2011, Bronen and Chapin 2013) have argued that shoreline protection exacerbates land erosion on adjacent land, others (e.g. Andrachuk and Smit 2012) show evidence that erosion prevention measures are effective in the long run. A systematic review of northern high-latitude coastal erosion controls is therefore necessary to understand which measures have worked and which did not.

This paper reviews the current erosion control practices being applied globally, with a focus on northern high-latitude communities (primarily in Alaska due to data availability), and explores potential measures that can effectively prevent or slow coastal erosion in northern high-latitude communities. Within this paper we (1) summarize the challenges in constructing erosion control measures in northern high-latitude regions and the solutions proposed in the literature, (2) synthesize and conduct a meta-analysis on case histories from scientific and gray literature publications both in permafrost and non-permafrost regions, (3) discuss the rationale, benefits, limitations, and costs of applying each prevention technique, (4) explore emerging techniques and technologies, and (5) identify the knowledge gaps in prevention of coastal erosion at northern high latitudes. The innovative techniques include those that have been tested in full-scale, small-scale research projects, laboratory settings, and numerical models. The costs of the current coastal erosion prevention measures are included to reflect the unit cost increase over the years in Alaska. The goal of this research is to assess past attempts at prevention and control of erosion along northern high-latitude coasts, so that this review may be used as a reference for decision-making for mitigating the impacts of erosion in northern high-latitude coastal villages in the future.

## 2. Data compilation of erosion control measures

The case histories and research studies of erosion control projects in this study are compiled from journal and conference articles and government documents. The databases that have been searched include the Northern Region Projects by the Alaska Department of Transportation and Public Facilities (ADOT&PF), documentation of Alaska Baseline Erosion Assessment by U.S. Army Corps of Engineers (USACE), the Denali Commission Project Database, and the documentation of Emergency Watershed Protection Program by Alaska Natural Resources Conservation Service (NRCS). According to USACE (2009d), other agencies such as the National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), Federal Emergency Management Agency (FEMA), Bureau of Land Management, and U.S. Forest Service only occasionally assisted with erosion control projects in the Alaskan coastal communities. As a result, most of the protection measures in the Alaskan coastal communities that are discussed herein are extracted from the USACE database.

## 3. General challenges of construction at northern high latitudes

There are many challenges in the construction in the remote northern high-latitude coastal regions, including remoteness of construction sites, limited construction material, and extreme environmental conditions (see summary in supplementary table S1 (available online at [stacks.iop.org/ERL/0000/0000/mmedia](https://stacks.iop.org/ERL/0000/0000/mmedia))). Challenges can be grouped into three main categories: geographic challenges, engineering challenges, and socio-economic challenges. Geographic challenges include site remoteness, extreme weather, highly variable site conditions, and short construction period. The engineering challenges include unavailability of equipment and instrumentation, unavailability of local construction materials, and limited database (e.g. documentation of environmental parameters and soil parameters, design and construction guidelines of erosion control measures that are specific to permafrost coastlines, and case studies of well-engineered northern high-latitude coastal structures). The socio-economic challenges consist of policy inadequacy, low labor retention, and vandalism. Solutions that are proposed in this paper and by those from the literature are synthesized accordingly to each challenge in supplementary table S1.

## 4. Coastal erosion processes at northern high latitudes

Erosion control structures should be selected and designed according to the types of coastal settings at a

site in order to optimize the structure performance. It is therefore important to understand coastal erosion processes that are specific to northern high-latitude sites. Permafrost-affected sandy beaches at northern high-latitudes are dominated by erosion processes common in non-permafrost regions such as steepening of foredunes and transport of beach sediments on gently sloping shores (Farquharson *et al* 2018). In contrast, where ice-rich permafrost is present, thermal abrasion is the main coastal erosion process. Aré (1988) defined thermal abrasion as erosion of ice-rich permafrost coasts due to combined mechanical and thermal action of waves at the underwater bluff base. Thermal abrasion then leads to the development of a wave-cut niche, leaving a cornice overhanging and eventually collapsing under its self-weight (Aré 1988, Hoque and Pollard 2009, 2016). This feature, which is unique to ice-rich permafrost coasts, is known as the block failure. Processes that are also unique to coasts affected by permafrost are thermally based and include thermal denudation and thermal settling. Thermal denudation is the destruction of shore cliffs under the action of thermal energy of air and solar radiation; while thermal settling is the deepening of littoral zone of the sea due to the thermal action of sea water, whose temperature depends on the air temperature, solar radiation, and ocean currents. As erosion progresses and leads to the landward migration of the shoreline, deeper terrestrial permafrost that persists below the level of coastal erosion may then become sub-sea permafrost (Overduin *et al* 2014).

The duration of coastal processes also varies seasonally and annually across the northern high-latitude coasts due to variability in the duration of sea ice coverage. In northern high-latitude regions not affected by sea ice, the open sea duration is year-long, similar to that at middle and low latitudes. In regions affected by sea ice, erosion is limited to the ice-free months but the degree of erosion is generally affected by seawater temperature and salinity and other arctic features such as pressure ridges, coastal geomorphology, and sea ice (Overduin *et al* 2014). Pressure ridges, if grounded with their keels extending to the nearshore bottom, can shelter shores from wave action and protect adjacent shorelines from further sea ice pressure (Taylor 1978). Nearshore profiles can easily be destabilized if the grounded pressure ridges are eroded by increased wave action owing to the decline in sea ice extent (Taylor 1978). Sea ice in various forms (e.g. ice pileup, landfast ice, and drift ice) can extensively modify the coastal morphology. For examples, ice pileup can gouge up sediments onto the land and restore beaches (Kovacs 1984) but can also erode the lower shoreface (Radosavljevic *et al* 2016) and damage coastal protection structures. Whereas, sea ice and landfast ice help prevent thermal abrasion (Mahoney *et al* 2007, 2014, Günther *et al* 2015). Unfortunately, the current decline in landfast ice and

sea ice has rendered the permafrost coasts more susceptible to erosion. Such complex interactions among these arctic coastal features need to be accounted in the design of coastal protection structures.

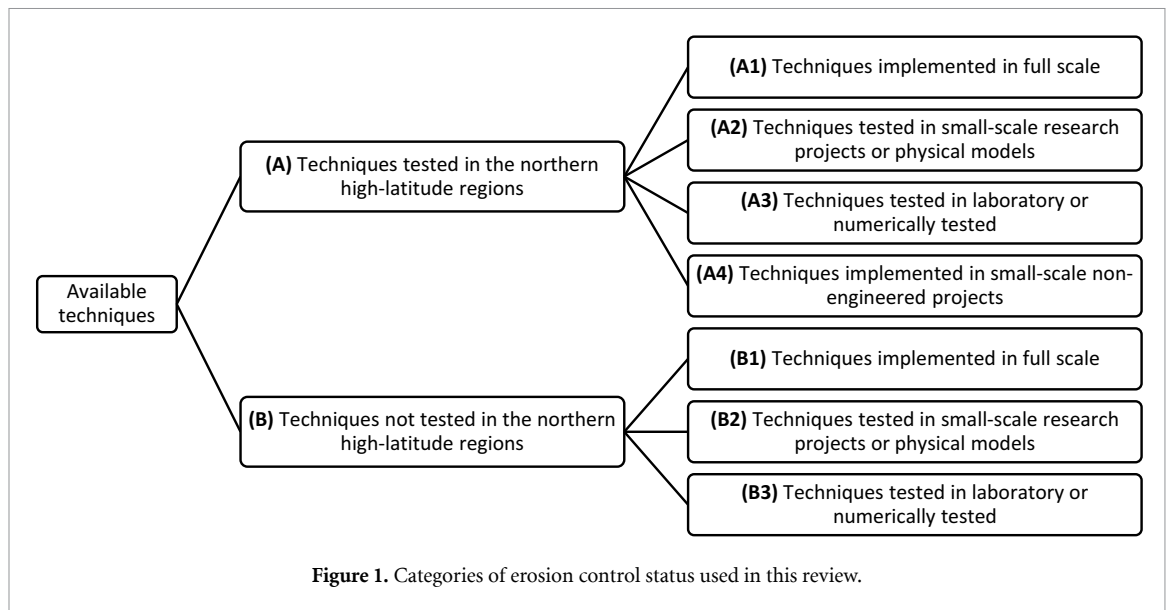
In general, northern high-latitude coasts can be categorized into lithified (i.e. rocky) and unlithified coasts, depending on the regional histories of glaciation. Unlithified coasts, which have high ground ice content and are usually composed of fine-grained soils, are more susceptible to erosion. It was reported in Overduin *et al* (2014) that the annual mean rate of erosion (0.4–1.1 m/year) is the highest along the Beaufort and East Siberian coasts, where unlithified ice-rich low-height bluffs are the common coastal type. As expected, Canadian Archipelago, Greenland, and Svalbard, where lithified coasts dominate, have the lowest annual mean rates of erosion (0.0 m/year) (Overduin *et al* 2014). While the mean rates at these locations are low, it is important to note that they are averaged over a great distance of coastline and may not represent the local erosion.

## 5. Past attempts to improve understanding of coastal dynamics and site reconnaissance for mitigating coastal erosion at northern high latitudes

Understanding of high-latitude coastal dynamics is critical to the design of effective erosion control measures. In the early 2000s, the Arctic Coastal Dynamics (ACD) program involving all circumarctic countries was established and has significantly contributed to the understanding of such dynamics through a series of workshop proceeding publications. Arctic coasts have been regionally classified and correlated with their rates of erosion; attempts have been made to identify arctic coast types most susceptible to erosion. Along the Alaskan Beaufort Sea coast, Jorgenson and Brown (2005) concludes that exposed bluffs have the highest mean annual erosion rates (2.4 m/year), whereas lagoons have the lowest rates (0.7 m/year). Mean annual rates of erosion is also higher for silty soils (3.2 m/year). The sediments are mostly sands and silts and the bluff heights are low (2–4 m) (Jorgenson and Brown 2005). Moving eastward to the Beaufort-Mackenzie region in Canada (Solomon 2005) and Barents and Kara Sea key sites in Russia (Vasiliev 2003, Vasiliev *et al* 2005), locations exposed to winds and high water level were also observed to erode at the highest rates. Erosion rates are also higher for coasts with high ground-ice content (Vasiliev *et al* 2005, Solomon 2003). However, erosion can be reduced if there are natural protections such as bars and flats (Solomon 2005, Gibbs and Richmond 2017).

Many have attempted to understand coastal dynamics along sea-ice and permafrost-affected coasts so that erosion and its impacts can be mitigated. Attempted approaches include developing an





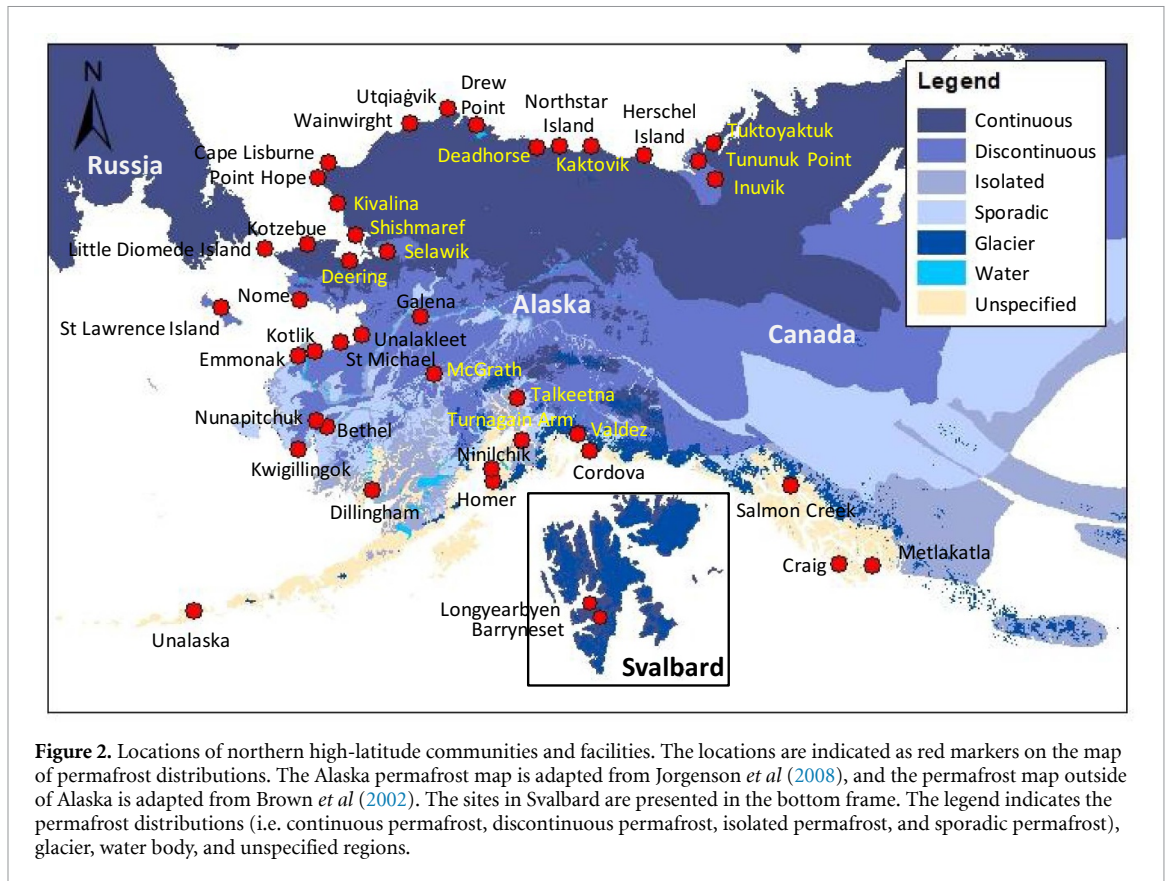
index of coastal erosion hazards (Solomon and Garreau 2003, Jordan 2003), utilizing satellite data for coastal erosion monitoring (Budkewitsch *et al* 2004), developing numerical models (Hoque and Pollardz 2004), seismic reconnaissance (Skvortsov and Drozdov 2003), and digital terrestrial photogrammetry (Wangensteen *et al* 2007) to predict bluff failure and erosion rates. Other than the environmental forcing factors, impacts of industrial exploitation on coastal erosion have also been investigated (Rivkin *et al* 2003, Ogorodov 2003, Sturtevant *et al* 2004). Significant efforts have been made to quantify the current and historical erosion rates across the pan-Arctic (e.g. Jones *et al* 2009a, 2009b, Arp *et al* 2010, Solomon 2005, Lantuit and Pollard 2008, Vasiliev *et al* 2005, Lantuit *et al* 2011, Günther *et al* 2012) so that hotspots of erosion hazard can be identified. Challenges of site investigation (Carter and Smith 2011, Smith and Carter 2011), data collection (Mason *et al* 2012), construction (Carter and Smith 2011, Smith and Carter 2011), and management (Smith 2008) in coastal regions in the Arctic were also reported.

## 6. Structural and non-structural erosion control measures

Damages from coastal erosion can be minimized by two different approaches: structural and non-structural measures. This paper includes only structural measures, which are defined in the United Nations General Assembly (2016) as measures that ‘reduce or avoid possible impacts of hazards and achieve hazard-resistance and resilience in structures or systems.’ Non-structural erosion control measures that ‘use knowledge, practice or agreement to reduce risks and impacts’ (United Nations General Assembly 2016) are not discussed in this paper.

Some examples of the non-structural measures are joining the National Flood Insurance Program (Smith 2008), implementing No Adverse Impact (Monday and Bell 2007), zoning, buyout acquisition, recovery or excavation of cultural sites, remediation of contaminated sites, relocation or elevation of at-risk structures, emergency warning system and signage, erosion control management, graduate education (Smith 2006), individual research efforts (Smith 2006), and community-based relocation (USACE 2018, Shearer 2012, Marino 2012, Bronen and Chapin 2013, Gorokhovich *et al* 2013, Maldonado *et al* 2013, Bronen 2015).

All structural erosion control measures presented in this article are classified into several categories as shown in figure 1. Two major categories are (A) techniques that are currently employed on northern high latitude coasts and (B) techniques that are not yet tested on northern high latitude coasts. Sub-categories that follow Categories A and B are techniques that have been implemented (1) in full scale, (2) in small-scale research projects or physical models, (3) in laboratories or numerical models, and (4) in small scale non-engineered projects. In this study, a structure is considered failing when it has been destroyed or displaced by environmental impacts (e.g. wave impacts, surges, sea-ice impacts, and permafrost thaw) and the repair would cost more than replacement. Another failure type refers to the ineffective measures where erosion exceeds the expected or predicted rates of erosion. A successful case refers to a measure that is not damaged or only slightly damaged when the encountered storm events are less severe than or equally severe to the design events. A measure is also considered successful if it is able to slow down or prevent erosion within the period of its designed service life when compared to adjacent sites with no coastal protection.



**Figure 2.** Locations of northern high-latitude communities and facilities. The locations are indicated as red markers on the map of permafrost distributions. The Alaska permafrost map is adapted from Jorgenson *et al* (2008), and the permafrost map outside of Alaska is adapted from Brown *et al* (2002). The sites in Svalbard are presented in the bottom frame. The legend indicates the permafrost distributions (i.e. continuous permafrost, discontinuous permafrost, isolated permafrost, and sporadic permafrost), glacier, water body, and unspecified regions.

## 7. Current erosion controls at northern high latitudes

Most case studies presented in this section are affected by coastal erosion while some are affected by fluvial erosion. Although these riverine communities are not affected by sea-ice and other processes specific to the coasts, the erosion control projects are affected by some similar factors unique to the northern high-latitude regions including remoteness, weather, and soil condition. So, the riverine experience may be helpful to the coastal communities and is therefore included in the discussion. The locations of northern high-latitude communities and facilities are presented in figure 2 with permafrost distributions as the base map. Figure 2 is adapted from the permafrost distribution maps by Brown *et al* (2002) and Jorgenson *et al* (2008).

Most of the measures that have been employed in Alaskan coastal villages and other infrastructure locations are hard structures such as revetments, bulkheads, seawalls, groins, and offshore berms. Figure 3 shows examples of these measures at northern high latitudes. The permafrost distributions (i.e. continuous, discontinuous, sporadic, and isolated permafrost) were identified for each site as indicated as superscripts in the column titled 'Location' in supplementary table S2. Thus far, revetments built with various types of materials have been the most common option in preventing coastal erosion at northern high

latitudes as presented in supplementary table S2. The materials include rocks (figure 3(a)), sandbags (figure 3(b)), articulated concrete mats (figure 3(c)), Core-loc™ units, timbers, and gabions. Among all materials, revetments built with rocks have been implemented and tested in the harsh Arctic environment and were observed to have fewer failure cases. Revetments built with sandbags have also been proven effective as temporary and semi-permanent measures. USACE (2009c) has conducted physical models to further optimize the stability of revetments built with sandbags. In general, revetments usually require maintenance throughout their service life as they can be easily displaced and destroyed during storm events or by sea-ice floes. Despite this limitation, revetments are preferred over seawalls, bulkheads, and other offshore structures due to the low costs and easy construction, inspection, and decommissioning (USACE 2018).

Seawalls (figure 3(d)) and bulkheads (figures 3(e)–(f)) have also been constructed in northern high-latitude coastal communities. Similar to revetments, bulkhead and seawalls protect permafrost bluff faces from the development of niches, a critical stage in shoreline collapse (Hoque and Pollard 2009, USACE 2018). For bulkheads, only one successful case using vertical sheet-piles is found in the literature review (USACE 2009a). Bulkheads made of Longard tubes™ and pipe-piles were easily subjected to vandalism (Shah 1982) and excessive deflection



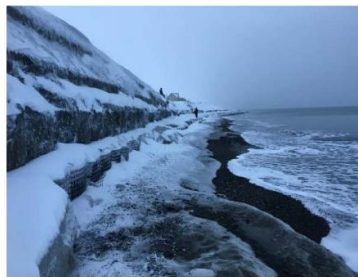
(a) Rock revetment  
(Cape Lisburne, Alaska)



(b) Revetment using sandbags  
(Kaktovik, Alaska)



(c) Revetment using articulated concrete mats  
(Tuktoyaktuk, N.W.T.)



(d) Seawall using gabion baskets with rocks  
(Utqiagvik, Alaska)



(e) Bulkhead using sheet-piles  
(Tununuk Point, N.W.T.)



(f) Bulkhead using pipe-piles  
(Bethel, Alaska)



(g) Sand berms  
(Utqiagvik, Alaska)



(h) Sandbags  
(Utqiagvik, Alaska)



(i) Metal scraps  
(Kivalina, Alaska)



(j) Tar barrels/drums  
(Kivalina, Alaska)

**Figure 3.** Various types of erosion control measures that have been employed at northern high latitudes. The photos were all taken at communities in the northern high-latitude regions. Image courtesies of U.S. Army Corps of Engineers, Alaska District (a), (b), (f), Dustin Whalen (c), Alaska Division of Homeland Security and Emergency Management (d), Worley Parsons (e), Millie Hawley (©2005) (i), and Janet Mitchell and Center for a Better Life (j). (g) to (j) are non-engineered expedient measures carried out during emergency.



(USACE 2007a, 2009d), respectively. Whereas, one successful case using a seawall made of logs is found to be effective in mitigating fluvial erosion where the crib walls were constructed (USACE 2007h). Seawalls made of gabions were not as effective due to potential sagging and settlement (USACE 2009b); while seawalls made of sheet-piles were not cost-effective, for example, a sheet-pile wall in a project proposal was estimated to cost more than \$31 million (in 2007 US dollars) for a 1 km long coastline (USACE 2007k). The groin system is a less common option in northern high-latitude coastal communities with only one case study presented in supplementary table S2. Due to their complex offshore construction, groins are especially vulnerable to damage from sea-ice (USACE 2018). This paper is unable to identify a successful case study that used groin systems alone to mitigate erosion impacts. The erosion in Tuktoyaktuk in northwestern Canadian Arctic was reduced when the groin systems were installed together with bulkheads (Shah 1982). Similar to groin systems, offshore berms are not preferred at northern high latitudes due to costly and complex offshore construction. This option was once considered in the feasibility report in Kivalina but was eventually eliminated (USACE 2007k). Overall, failures of seawalls, bulkheads, and groin systems are associated with displacement, deflection, settlement, vandalism, and material ruptures as presented in supplementary table S2.

In the event of an emergency, sacrificial structures have been constructed as expedient measures to minimize the erosion as shown in figures 3(g)–(j). The materials used in sacrificial structures include sandbags, supersacks, ripraps, sand berms, and root-wads. Although the materials are the same as those used in the construction of hard structures, these sacrificial structures are ineffective when they are not properly designed and constructed. When in short supply, these materials are substituted using scrap metal and concrete and other waste materials. Such materials can potentially cause pollution. Based on the case histories presented in supplementary table S2, these measures are often ineffective in preventing or slowing erosion and require maintenance after each storm event (USACE 2007a, 2007d, 2007f, 2007g, 2007j, 2008b, 2018, Jaskólski *et al* 2018) and may sometimes exacerbate the adjacent coastline due to material mining (Carter and Smith 2011). Root-wads and willow planting are the only case histories that have been effective in preventing erosion, but the project is located in Cordova, which is a non-permafrost region of Alaska affected by riverbank erosion as shown in table S2 (USACE 2007a, Smith 2008).

Soft structures such as beach nourishment and dynamically stable beaches have also been implemented at northern high-latitudes. Beach nourishment requires continual sources of sand and is effective only when there are existing sources of sand

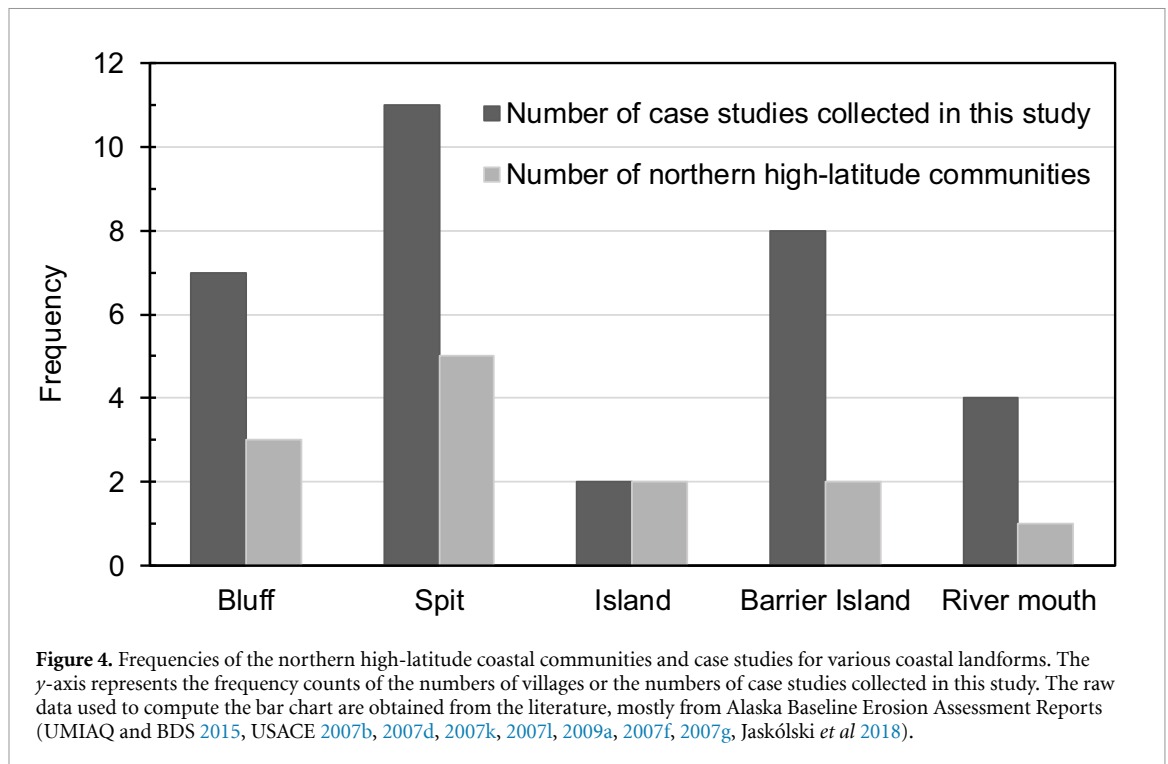
adjacent to the sites. This solution is rarely used in northern high-latitude communities given the lack of local sand sources, transportation challenges and costs, the depletion of local construction materials, and the environmental issues brought by sand mining. As a result, only a few beach nourishment projects have been carried out along northern high-latitude coasts and these are presented in supplementary table S2. Beach nourishment is effective in Homer, Alaska (a non-permafrost region), but ineffective in Utqiagvik, Alaska (a continuous permafrost region) where the storm events are more intense and sea ice can interfere with sand transport of the nourished beaches.

The other soft structure that has been implemented in northern high-latitude coastal communities is the dynamically stable beach. Specifications of the three dynamically stable beaches constructed in Alaska were presented by Smith and Carter (2011) and are summarized in supplementary table S2. Coarser sediments such as rocks, concrete armor units, and cobbles were used. The main difference between a dynamically stable beach and a nourished beach is that the former is designed according to the wave direction and is designed to be shaped by future storm events to reach equilibrium over time. Only minimal maintenance is needed for dynamically stable beaches, depending on the intensity of the storm events, whereas another beach-filling is needed for the nourished beach to continue its function after the first storm event. According to Smith and Carter (2011), all three dynamically stable beaches (i.e. one in Unalakleet, a village located on a spit near a river mouth in the discontinuous permafrost region of Alaska, and two in Unalaska and Homer in the non-permafrost affected region) have performed well and do not require high maintenance after storm events.

## 8. Meta-analysis of current measures with site characteristics

### 8.1. Coastal landforms

Alaskan coastal communities mostly reside at landforms such as bluffs with narrow beaches, spits, islands, barrier islands, and river mouths. Among the various landforms, spits are the most frequently resided (5 out of 13 locations collected in this study). In figure 4, the frequencies of northern coastal communities at various coastal landforms are plotted in light gray; the frequencies of erosion control case studies (total number  $n = 32$ ) collected in this study were plotted in dark gray. The frequency of the case studies indicate that more measures had been repeatedly constructed in barrier islands and spits. In general, the soil materials in villages range from silts, fine sands, sands, to cobbles. Little Diomed Island, which is an exception, is rich in rocks and boulders.



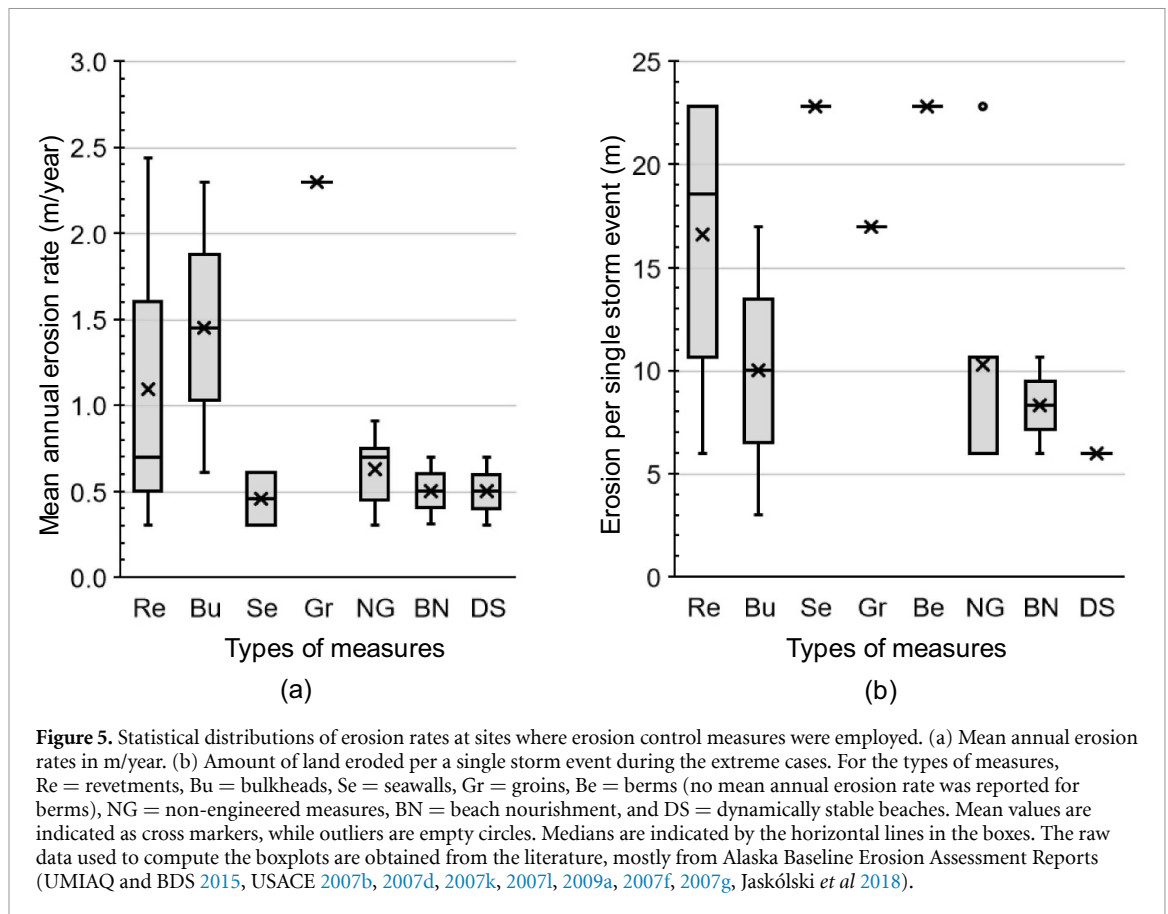
### 8.2. Rates of erosion

Figures 5(a)–(b) shows boxplots of the mean annual erosion rates and erosion per single storm event reported at sites where the erosion controls were implemented. Numeric data used to generate the plots are included in supplementary table S3. As illustrated in figure 5(a), revetments and bulkheads have been employed for sites with a wide range of mean annual erosion rates (0.3–2.4 m/year). As expected, groin systems, which are an offshore structure, have been employed at sites with high mean annual erosion rates (2.3 m/year); whereas, beach nourishment, dynamically stable beaches, and other non-engineered measures have been employed at sites with low mean annual erosion rates (0.3–0.9 m/year). However, seawalls were employed at sites with low erosion rates (0.3–0.6 m/year). It could be possible that seawalls were constructed in these sites to slow erosion after extreme episodic erosion (figure 5(b)). Similarly, for revetments and bulkheads, the erosion reported per single storm event also ranged widely from 3.0 m to 22.9 m. The episodic events of erosion were at the lower ends for beach nourishment, dynamically stable beaches, and other non-engineered measures (6.0–10.7 m) with an outlier of 22.9 m for non-engineered measures. Seawalls, groins, and berms had been constructed at sites with high episodic erosion (17.0–22.9 m).

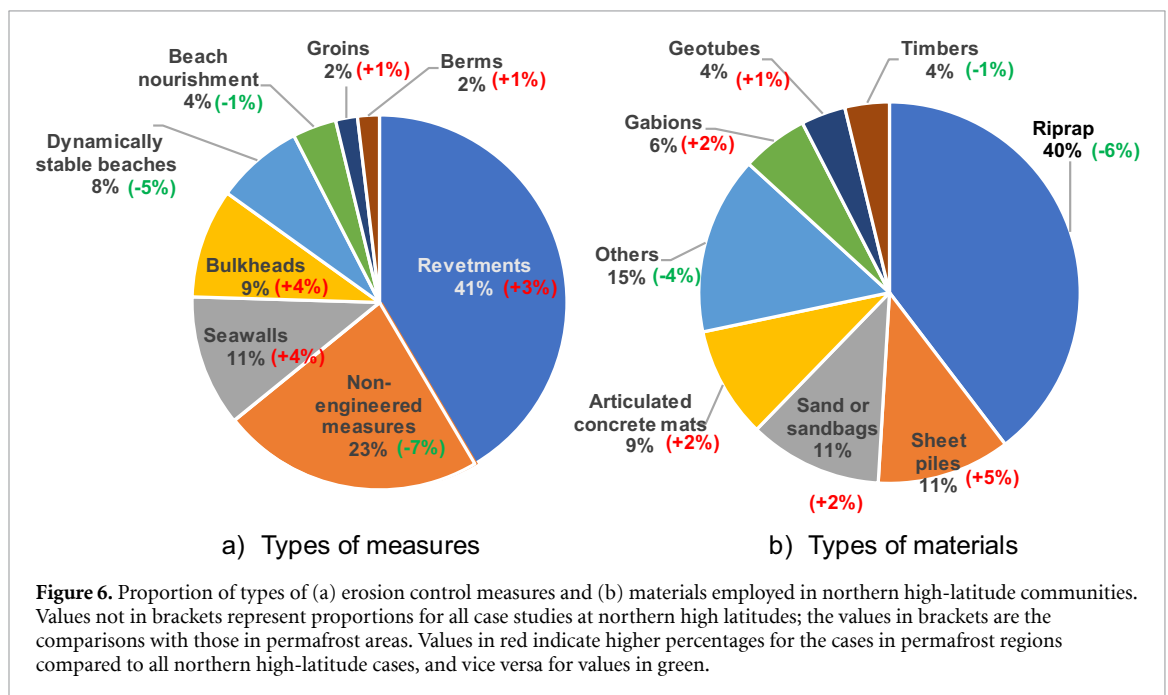
### 8.3. Proportions of various types of measures

Figure 6(a) shows the proportion of the types of erosion control measures employed in the northern high-latitude coastal and riverine communities. Based on a total of 53 cases, revetments were most

frequently employed (41%) and non-engineered measures were the second (23%). The measures that came after non-engineered measures are seawalls (11%), bulkheads (9%), dynamically stable beaches (8%), beach nourishment (4%), groins (2%), and berms (2%). Among the 53 cases at northern high latitudes, 38 of them were employed within permafrost regions (including continuous, discontinuous, sporadic, and isolated permafrost). For the rest of the cases ( $n = 15$ ), although they are influenced by northern high-latitude climate, they are located within non-permafrost regions. For the cases in permafrost regions, the percentage of revetments increases to 44% whereas the percentage of non-engineered measures reduces to 16%. Similarly, figure 6(b) shows the proportions of the types of materials. Among all the cases collected in northern high-latitude regions, riprap is the most frequently used material, accounting for 40% of the materials. Sand or sandbags and sheet piles are both the second (11% for each). For cases in permafrost regions, the percentage of riprap reduces to 34%, but both percentages of sand or sandbags and sheet piles increase to 13% and 16%, respectively. The percentage differences between counts in northern high-latitude regions and those in permafrost-affected northern high-latitude regions are indicated on the pie charts in brackets. The percentages of the measures (in table 1, the column ‘Grouped percentages’) computed in this study are compared to those (in table 1; the last column) reported in a survey ‘Alaska Community Erosion Survey’ conducted by USACE (2009f). In this survey (USACE 2009f), the Alaskan coastal communities were asked to indicate the types of materials



**Figure 5.** Statistical distributions of erosion rates at sites where erosion control measures were employed. (a) Mean annual erosion rates in m/year. (b) Amount of land eroded per a single storm event during the extreme cases. For the types of measures, Re = revetments, Bu = bulkheads, Se = seawalls, Gr = groins, Be = berms (no mean annual erosion rate was reported for berms), NG = non-engineered measures, BN = beach nourishment, and DS = dynamically stable beaches. Mean values are indicated as cross markers, while outliers are empty circles. Medians are indicated by the horizontal lines in the boxes. The raw data used to compute the boxplots are obtained from the literature, mostly from Alaska Baseline Erosion Assessment Reports (UMIAQ and BDS 2015, USACE 2007b, 2007d, 2007k, 2007l, 2009a, 2007f, 2007g, Jaskólski et al 2018).



**Figure 6.** Proportion of types of (a) erosion control measures and (b) materials employed in northern high-latitude communities. Values not in brackets represent proportions for all case studies at northern high latitudes; the values in brackets are the comparisons with those in permafrost areas. Values in red indicate higher percentages for the cases in permafrost regions compared to all northern high-latitude cases, and vice versa for values in green.

that have been used in their communities to prevent coastal erosion. The results reported in this paper, which were computed based on case studies reported in the literature, were comparable to the survey with riprap (including rocks and cobbles) being the most frequently used measures and geo-tubes being the least popular option.

**8.4. Effectiveness of current measures reported in community survey**

In the same survey by USACE (2009f), the communities were asked about the effectiveness of the erosion control measures currently employed in their communities; 84% of the community respondents ( $n = 44$ ) indicated that the measures had been

**Table 1.** Percentages of various types of measures discussed in this study and percentages of measures covered by the 2009 USACE survey data.

Materials		This study			USACE survey (USACE 2009f)
		Percentages (%) (within permafrost region only)	Percentages (%) (all cases)	Grouped percentages (%)	Percentages (%)
Riprap	Rocks	34	36	40	30
	Cobbles	0	4		
Gabions		8	6	6	9
Sand or sandbags		13	11	11	8
Articulated mats		11	9	9	6
Geotubes		5	4	4	1
Others	Sheet piles	16	11	30	46
	Timbers	3	4		
	Others	11	15		

effective. The communities were further asked about whether there had been a failure in the past in their communities; 100% of the respondents ( $n = 23$ ) indicated that there had been a failure. In general, the communities reported that the current measures cannot fully prevent erosion, are not adequate for large scale protection, and have been heavily damaged due to lack of repair and maintenance. It is likely that these past measures were designed without adequate site investigations and without the considerations of the changing climate. As a result, these measures were only able to prevent mild constant erosion but not extreme erosion in an episodic manner and may fail in future storm events.

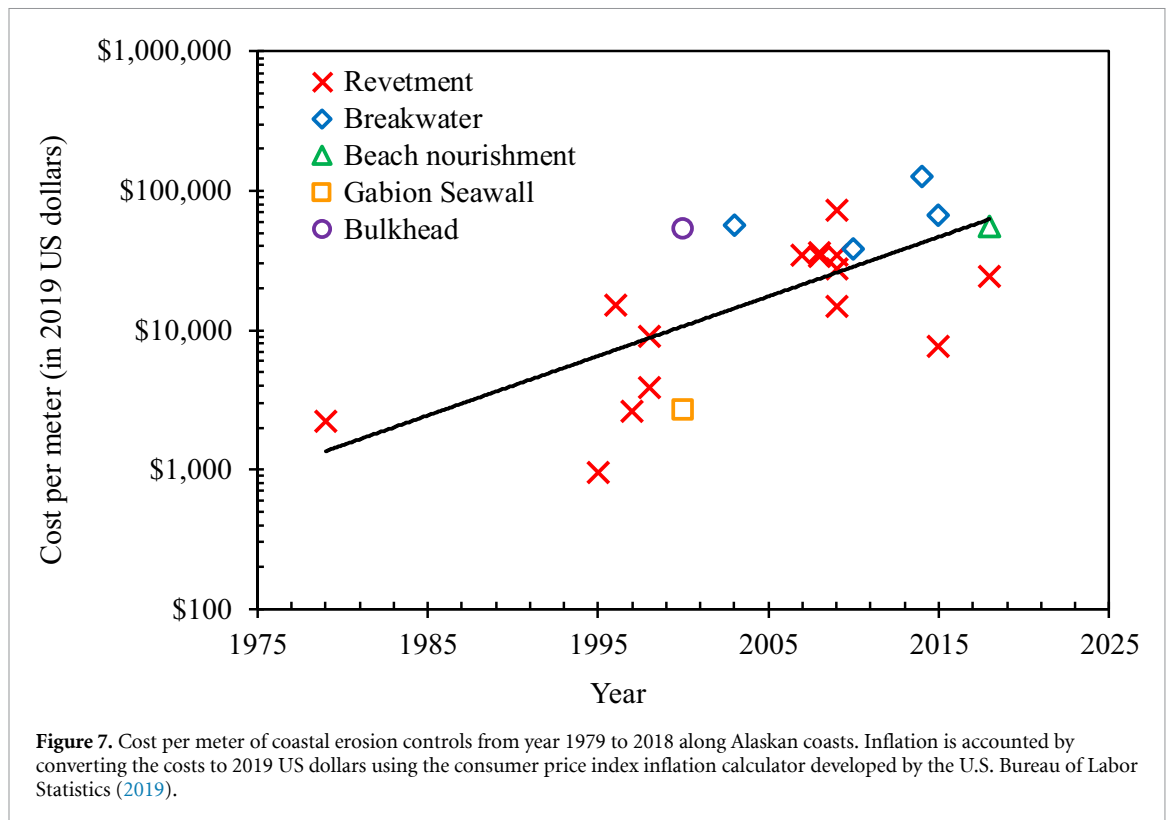
### 9. Costs of erosion control measures at northern high latitudes

The cost of erosion controls in Alaska has been escalating over time even for the expedient measures that were built during the planning of community relocations such as those in Kivalina and Shishmaref (USACE 2009d). Supplementary table S4 shows the type of protection measure for each case history and the corresponding length of the structure, cost, and year of construction. The map of permafrost distributions developed by Brown *et al* (2002) and Jorgenson *et al* (2008) were used to identify permafrost distributions (i.e. continuous, discontinuous, sporadic, and isolated permafrost) for each site as indicated as superscripts in the column titled 'Communities in Alaska' in supplementary table S4. The cost per meter of erosion control measures that have been implemented or recommended in the feasibility studies are plotted in figure 7 over 40 years from 1979 to 2018. Inflation is accounted by converting the costs to 2019 US dollars using the Consumer Price Index Inflation Calculator developed by the U.S. Bureau of Labor Statistics (2019). It is important to note that the impacts and concerns on coastal communities and facilities predate the 40-year time interval,

dating back to the well-known 1963 storm event in Utqiagvik, Alaska; this storm event is widely used as a historical reference in the North American literature. However, this 40-year time interval was selected mainly because of the availability of reports and documents specific to coastal protection structures. The early review paper by Aré (1988) might have inspired more efforts (and therefore more documentation) to be made in the field of coastal erosion protection since then.

As shown in figure 7, the unit cost has increased (approximately 10% increase per year) in the past four decades. The costs of breakwaters (figure 7, blue diamond-shaped markers) and bulkheads (figure 7, purple circle marker) are above the average cost. The cost of gabion seawall construction is below average and beach nourishment falls on the average cost. Although the estimated cost of the beach nourishment seems to fall within the median range as shown in figure 7, its cost is considerably high when compared to the average cost in mid- to low-latitude regions. For an 8 km shoreline in Utqiagvik, AK (USACE 2018), for example, the initial cost of the beach nourishment was estimated at \$297 431 000 (in 2018 dollars). This results in a cost of approximately \$37 000 per meter for initial construction. However, in mid- to low-latitude regions, the initial construction cost for beach nourishment ranges from only \$6600–\$16 000 per meter of coastline (SAGE 2015). This infers that the initial cost to practice beach nourishment in a northern high-latitude region is at least 2 times the cost needed for a mid- to low-latitude region. Similarly, in mid- to low-latitude regions, the initial construction cost for bulkheads ranges from \$6600–\$33 000 per meter (SAGE 2015). However, the bulkhead in Dillingham, Alaska, which is a northern high-latitude village affected by fluvial erosion, costs about \$53 000 per meter in 2019 US dollars (USACE 2009d). This is equivalent to a cost that is approximately 1.6 to 8 times higher than the cost needed for a similar application at middle to low latitudes.





### 9.1. Meta-analysis of cost of erosion control measures

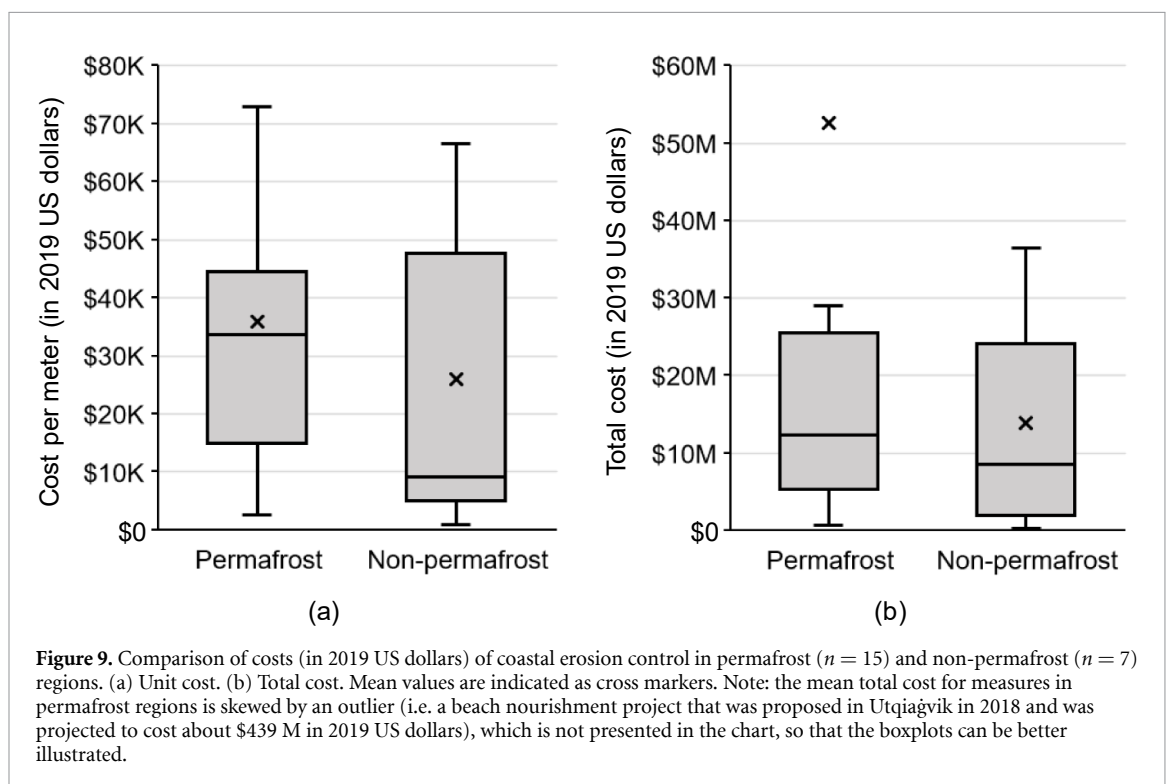
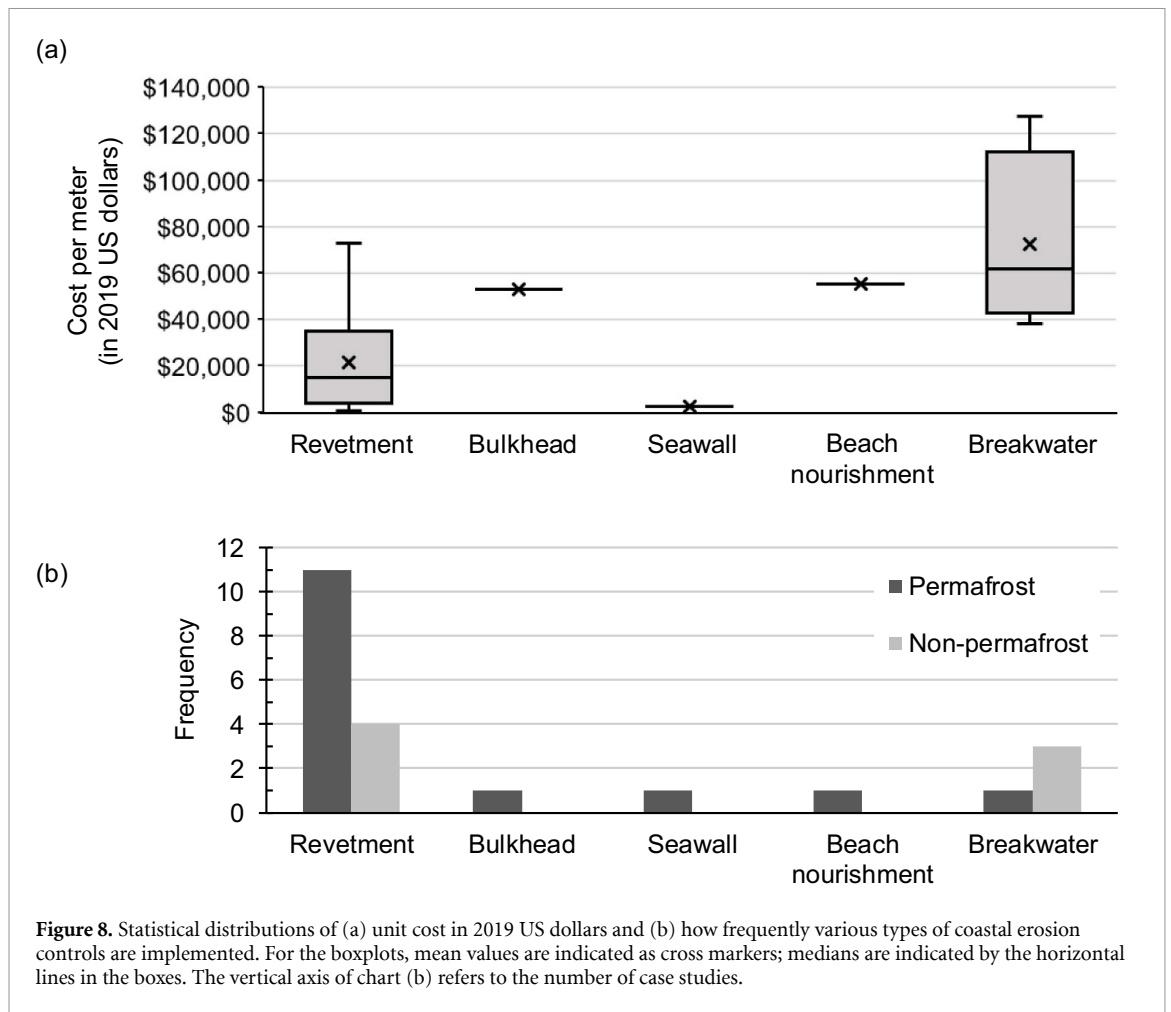
A statistical analysis was further performed on the case studies with reported construction cost (figure 8). As expected, breakwater, which is an offshore structure, has higher median cost than the other measures (figure 8(a)). Such trend is much clearer when comparing breakwater to revetment but not the other measures since only one data point is available for bulkhead, seawall, and beach nourishment. The low unit cost of revetments may be one of the reasons that lead to the popularity of revetments (as illustrated by the high frequency of revetment in figure 8(b)) in controlling coastal erosion in Alaska.

Although breakwater, which is mostly constructed in non-permafrost regions, has a higher median cost, the cost (both unit and total costs) of erosion control measures in permafrost regions is higher (in figures 9(a) and (b)). This is likely because a revetment costs more if constructed in a permafrost region, driving up the cost of overall measures. In addition, it is noted in figure 9 that the difference in medians between permafrost and non-permafrost is higher for the unit cost but not as much for the total cost. This is because the length of coastline protected by the measures in non-permafrost regions is generally longer.

## 10. Potential erosion control measures or techniques

The potential prevention measures or techniques that have been used in mid- to low-latitude regions or

assessed for their potential application in Arctic systems are synthesized and categorized into four different applications: geosynthetics, static bay beach concept, refrigerating techniques, and biogeochemical application. Geosynthetics have been implemented in full-scale applications in various forms to control coastal erosion in mid- to low-latitude regions as shown in supplementary table S5. They were used as offshore structures (e.g. breakwaters) and onshore structures (e.g. sand-bagged seawall, sand-bagged revetments, and wrap-around revetments). Martinelli *et al* (2011) observed that high-density polyethylene (HDPE) sandbags when constructed as submerged barriers resisted a strong storm surge in Emilia-Romagna, Italy in December 1996 and stabilized a natural sandy beach profile. When constructed as a seawall, the sandbags resisted a significant wave height of 5 m (Corbella and Stretch 2012). Another type of geosynthetic application, revetments constructed using Geotube® units, prevented erosion at a localized segment of coastal bluff (Nickels and Heerten 1996, Yasuhara *et al* 2012). Geotube® units can be a potential protection measure during emergencies given its short construction duration of less than one hour per Geotube® (Shin and Oh 2007). Another emerging geosynthetic application is geotextile wrap-around revetments (GWR). The GWR structure in Sylt Island in Germany was effective in resisting wave action during intense storm events in 1993 and 1994 and prevented coastal erosion by more than 10 m when compared to adjacent coastlines (Nickels and Heerten 1996, Yasuhara and Recio-Molina 2007, Yasuhara *et al* 2012). Although the



sand-covered structure was exposed after the storm events, it was not damaged. Small-scale geosynthetic applications incorporating geotextile bags with conventional methods (e.g. breakwater) have been implemented in some northern high-latitude sites. The geotextile sandbags were designed and installed in Longyearbyen and Barryneset in Svalbard in 2005 for an experiment to develop geosynthetic products for cold climates (Caline 2010). The USACE (2009c) started to consider using geosynthetic applications along the Alaskan coasts given the successful case studies across low to high latitudes.

The static bay beach concept (SBBC), as synthesized in supplementary table S6, is similar to the dynamically stable beach presented in supplementary table S2. This application mimics the shapes of natural bays and beaches. It prevents erosion by allowing a shoreline to reach static equilibrium through incorporations of natural or artificial physiographic features (preferably a headland). Several case studies in northern high-latitude regions have demonstrated the effectiveness of the static bay beach concept. While the principle employed is the same at both the permafrost and non-permafrost sites, relatively coarse fill materials were selected and used for the permafrost sites in order to dissipate greater wave energy. The benefits of the static bay beach are its low costs and its satisfactory performances in the long term when compared to other hard measures (Hsu *et al* 2010, Carter and Smith 2011).

Refrigerating systems such as thermosyphons have traditionally been utilized at permafrost sites to improve the stability of roadbeds and embankments (Regehr *et al* 2012). There are three different types of thermosyphons: active, passive, and hybrid. An active thermosyphon uses a heat pump to transfer heat (Wagner 2014). A passive thermosyphon uses working fluid to transfer heat from its evaporator (in the ground) to its condenser and radiator (above the ground) when air temperature is lower than the ground temperature (Gudmestad *et al* 2007); this heat transfer process does not utilize external power and ceases during the summer when the air temperature is higher than the ground temperature. A hybrid thermosyphon integrates the functions of both active and passive thermosyphons and operates with natural convection during winter months (when air temperatures are sufficiently low) and with a heat pump during summer months (when air temperatures are above 0 °C). According to Dupeyrat *et al* (2011), an increase in ground temperature can cause the frozen ground to thaw. Such phase change of ice within the permafrost results in excess water content, which in turn reduces the cohesion and shear strength of permafrost. So, the erosion resistance of thawed soil decreases; as a result, the rate of erosion increases. In brief, erosion can be potentially prevented or reduced if ice-bonded sediments can be kept below its freezing point. To date, this technique has only

been applied in small scale to improve the stability of critical infrastructure such as the communication towers in Kwigillingok, Alaska, the power plants in Utqiagvik, Alaska, the hangar facility in Deadhorse, Alaska, and the college in Inuvik, Canada (Wagner 2014). Recently, a thermosyphon system with 3 meter spacings was also proposed to mitigate river erosion in Kotlik in the sporadic permafrost zone of Alaska, but the proposal was eventually eliminated due to the high cost (Roberts *et al* 2019). Although conventional thermosyphons (typically installed with 3 m spacings) cost about \$1 M per km, they require minimal maintenance throughout their service life. Zottola (2016) proposed to use two-phase passive thermosyphons to alleviate coastal erosion through freezing near-thawing soils. The numerical models with soil and climate data from Drew Point and Utqiagvik, Alaska as input parameters showed that thermosyphons are capable of slowing permafrost coastal erosion (Zottola 2016) but further refinement of the design is needed to optimize its cost. Detailed information for the case studies of thermosyphons are summarized in supplementary table S7.

The microbial application is an emerging technique that has been applied to control internal and surface erosion and its overall effectiveness has been rated highly (Dejong *et al* 2013). Many research studies have focused on developing the technique to be ready for real-world applications, and some studies have begun to investigate the performance of microbial application at coastal bluffs and sand dunes to mitigate coastal erosion (Phillips *et al* 2013, Imran *et al* 2019, Shahin *et al* 2020). Detailed information of the two case studies that may be applicable to the northern high-latitude sites are presented in supplementary table S8. One of them is a bench-scale project, investigating the performance of *sporosarcina pasteurii* in mitigating erosion of sandy soils of foreshore slopes and sand dunes (Salifu *et al* 2016, Shanahan and Montoya 2016, Shanahan 2016). *Sporosarcina pasteurii* is a bacterium with the ability to precipitate calcite and cement sand particles given a calcium source and urea, through the process of microbiologically induced calcite precipitation (MICP) or biological cementation. The treated soils showed above-moderate unconfined compressive strength and improved the performance of sand dunes under wave-simulation. The wave-action-induced erosion was significantly reduced when the sand was treated with a microbial solution (Salifu *et al* 2016). The other study was conducted using native microbes to cement sand to develop artificial beach-rocks that are durable enough to replace concrete structures in erosion control projects (Khan *et al* 2015, 2016); coral sand and ureolytic bacteria from beach-rocks in Nago, Japan were used in the study. An average unconfined compressive strength of 12 MPa was achieved for the artificial beach rocks after 14 d of curing.

This technique can potentially resolve the shortage of local quarries in remote northern high-latitude villages and control the escalating cost of rocks and ripraps.

## 11. Research gaps and challenges

To date, the potential erosion control measures and techniques described in the previous section have not been fully tested in the northern high-latitude regions. Some of them have not been evaluated even under the laboratory-simulated northern high-latitude conditions. Here we assess their strengths and weaknesses within the northern high-latitude environment and identify research gaps that need to be filled before field implementation.

### 11.1. Geosynthetics

Among the potential erosion control measures and techniques that we researched, geosynthetics currently have the greatest potential to be applied along the northern high-latitude coasts given their successful field applications in the past. Erosion has been controlled using geosynthetics from sparsely-located individual geosynthetic sandbags to well-designed seawalls constructed using geosynthetic materials. However, the main challenge of using geosynthetics is the prolonged UV exposure by 24 h daylight a day in the summer. Developing UV resistant and non-degradable geosynthetics is needed for northern high-latitude applications. Geosynthetic materials, which can be easily decommissioned, may be an effective option for temporary erosion control so that the threats to environment can be reduced (Sinitsyn and Recker 2019). However, if not properly monitored, the degraded geosynthetic materials can pollute the environment, posing threats to arctic wildlife. The degradation of geosynthetic materials in harsh and frigid northern high-latitude environments (e.g. impacts of ice-floes and prolonged exposure to sub-zero temperatures) can further complicate the problem by allowing brittle ruptures of sandbags to occur, resulting in sand leaking and excessive sand movement within the sandbags. Settlement and collapse of a seawall made of geosynthetic bags can occur if sand move excessively within those bags (Corbella and Stretch 2012). As a result, materials that remain flexible and non-brittle at low temperatures need to be identified; Caline (2010) therefore suggested that highly angular aggregates and those larger than 10 cm should be removed to avoid brittle puncture. Damage to geotextile sandbags by low temperatures or coastal ice can also be reduced by using thicker geotextile fabrics, but the seams on thick fabrics can be easily unpicked (Caline 2010). Therefore, the sewing machine and sewing threads need to be selected accordingly for the geosynthetics materials. In addition, the effects of sand movement on the overall

stability of the geosynthetic structures need to be evaluated. The optimal sand-filled volume also needs to be determined for different combinations of locally-available filling materials and geosynthetics materials.

### 11.2. Static bay beach concept

One of the challenges of static bay beach concepts is to develop a process-based shape equation that can accurately simulate a northern high-latitude coastline with various coastal features. If simulated coastline profiles are not consistent with the real profiles, northern high-latitude beaches at static equilibrium will be difficult to maintain and final maintenance costs will vary substantially from their respective initial estimations. The current shape equation (i.e. Gainza *et al* 2018) is capable of modeling complex bathymetry incorporating influences of near shore islands, rock outcrops, and rocky platforms. For a shape equation to be effectively applied to a northern high-latitude coastline, effects of headlands, bluffs, barrier islands, spits, and ice ridges on the nearshore need to be considered in the equation. Another challenge is to identify the control points when applying a shape equation (Lausman *et al* 2010) as the final prediction of a static equilibrium shoreline highly depends on the initial selection. As those coastal features degrade due to thawing of permafrost or melting of ice, so do the controls points. The SBBC application also becomes more challenging when environmental forcing factors (e.g. sea ice, wave fetch, storm patterns) are changing due to climate change processes. Effects of these changes need to be reconsidered to predict the long-term equilibrium coasts at northern high latitudes.

### 11.3. Refrigerating system

The challenges of implementing thermosyphons are mostly associated with their up-scale field application in terms of high transportation costs and complex installation as compared with those of the traditional hard structures. Besides, given the high initial implementation costs of thermosyphons, they must be appropriately selected so that their capacities are flexible enough to account for the future climate and permafrost warming conditions. During summer months when air temperature is higher than the ground temperature, the heat pump of an active or a hybrid thermosyphon system needs to be activated to continue the heat transfer process. Heat pump operation may consume more energy if the mean annual air and ground temperatures continue to rise in a warming climate. The possibility of utilizing green energy such as the solar energy can be explored to lower the fuel consumption.

### 11.4. Microbial application

One of the concerns of applying MICP to the soils in northern high-latitude regions is the efficacy of the precipitate formation under cold temperatures.



**Table 2.** Rationales of the potential erosion controls and the applicable soil types, coast types, and tidal environments.

Erosion controls	Rationales	Applicable soil types	Coast types	Tidal environments	Possible integration with conventional measures
Geosynthetics	To withhold soils and resist wave impacts and storm surges	Sand	Bluffs or fore-shores	High energy wave impact and strong surge	<ul style="list-style-type: none"> <li>• Geotextile sandbags for revetments</li> <li>• Geotextile wraps for revetments</li> <li>• Geo-tubes for revetments</li> <li>• Geo-tubes for groins</li> </ul>
Static bay-beach concept	To reshape beach materials to a state that is in dynamic equilibrium with wave action	Sand and gravel	Shores	Low energy setting and a single constant wave direction	<ul style="list-style-type: none"> <li>• Integration with revetments</li> <li>• Integration with beach nourishment</li> </ul>
Refrigerating techniques	To freeze or insulate thawing permafrost	Silt and peat	Bluffs	High energy setting if combined with sheet-pile walls or other equivalent measures	<ul style="list-style-type: none"> <li>• Integration with sheet-pile walls</li> </ul>
Microbial applications	To produce artificial rocks or to strengthen soils through the binding of soil grains.	Sand	Bluff if it is directly treated, or fore-shores if using beach-rocks	Low energy setting	<ul style="list-style-type: none"> <li>• Produce gravels or rocks for dynamically stable beaches</li> <li>• Stabilize sand berms</li> <li>• Stabilize sand dunes</li> <li>• Produce rocks for revetments</li> </ul>

As reported in Cheng *et al* (2016), calcite can still form on grain surfaces at a temperature as low as 4 °C using *Bacillus pasteurii* although the amount of calcite formed per unit weight of sand at the temperature of 4 °C is 25% lower than that at 25 °C and the unconfined compressive strength is 56% lower. Performances of the calcite precipitation at 4 °C have also been assessed by Jiang *et al* (2016) using *Bacillus megaterium* and purified urease enzyme. *B. megaterium* was selected over *Sporosarcina pasteurii* as the former is more versatile and can grow at low temperatures (Jiang *et al* 2016). Efficacy of the calcite precipitation at temperatures lower than 4 °C needs to be evaluated in future studies to minimize the thermal disturbances to both the active layer and permafrost and to maintain the desired urealytic rates. Gomez *et al* (2015) developed a stiff crust, which has a high resistance to erosion, in the field using *Sporosarcina pasteurii*. This technique can be tried and tested at a bluff face to form a crust, which can potentially prevent niche development at the toe and insulate the permafrost beneath. However, the challenges include calcite degradation under freeze-thaw effects and wave impacts.

## 12. Choosing the optimal measures or techniques

The potential erosion controls are summarized in table 2 with their corresponding rationales, coastal

types, tidal environments, and possible integration with conventional measures. The majority of the potential erosion controls are applicable to sandy coasts and are effective in a low energy setting. In the past Arctic coastlines (such as the North Slope of Alaska) were generally regarded as a low wave-energy environment where waves were damped by perennial sea ice cover (Owens *et al* 1980) these measures could be applicable to such shores. However, given that sea ice is now declining and high-latitude coastlines may transition into a more dynamic coastal system, these potential erosion controls may soon be inapplicable and need further development. Other than conventional solutions, the geosynthetic application could also be a good option for a high energy setting due to its several successful case histories in withstanding strong wave impacts and surges. Thermosyphon systems can also be used to dissipate high wave energy if integrated with sheet-pile walls or any equivalent measures. All of the potential erosion control measures and techniques discussed herein can be applied on the beach, except for the refrigerating systems, which are intended to be located on ice-rich permafrost bluff tops to keep them from thawing. The selection of erosion control measures is site-specific and is constrained by many factors such as cost, construction material availability, and contractors' skills and experience. At coastal sites where rocks are readily available, it may be more cost effective to continue to employ rock revetments to control erosion.

Other than effectiveness, many factors (e.g. total costs, construction material availability, and sustainability) should also be considered in selecting the optimal coastal erosion control measures for a site. The life cycle cost analysis (LCCA), which is a quantitative approach that selects optimal measures based on their total costs over the life cycle, has been the primary framework used by USACE and construction companies. The total cost in LCCA includes the initial construction costs, annual maintenance and repair costs, operating costs, and inspection costs. However, analyses based on merely the total costs may not be adequate and the environmental impacts should also be considered. Recently, the life cycle assessment (LCA), which assesses environmental performance and impacts of a measure over its life cycle, including raw material extraction, manufacturing, use, disposal and recycling, are of rising interest in civil engineering (Singh *et al* 2011, Dong and Frangopol 2016, Raymond *et al* 2019). A combined assessment that incorporates both environmental and socio-economic impacts can be helpful for choosing the optimal coastal erosion control measures and should be transferred to coastal and geotechnical engineering in northern high-latitude regions.

### 13. Conclusions

This study investigates the conventional techniques that are currently used for northern high latitudes and emerging erosion control techniques applied globally that can potentially be adapted to prevent or limit coastal erosion in northern high-latitude regions. Challenges of implementing erosion prevention measures in northern high-latitude regions are summarized into three categories: geographical, engineering, and socioeconomical categories; the corresponding solutions, which are proposed in the literature, are also systematically documented in this review.

Meta-analysis is conducted on the case studies collected from scientific and gray literature publications. Our analysis shows that revetments built with rocks have the least reported failures among the current erosion controls and are the most common (41% of all measures) and cheapest measures applied in northern high-latitude settings, when compared to other less successful hard measures such as seawalls, bulkheads, and groin systems. Riprap is the most frequently used materials, accounting for 40% of the measures. No successful case history has been reported for the non-engineered expedient measures that are constructed in northern high-latitude regions in the event of an emergency. The effectiveness of beach nourishment as a soft structure in permafrost regions is inconclusive. However, dynamically stable beaches, which are also a soft structure, are effective in preventing erosion; observations show that they experience only minor damages after single storm events.

Based on the collected case studies, we found that spits are landforms most frequently resided by the Alaskan coastal communities and more measures had been constructed on spits. Revetments have been implemented at sites with a wide range of mean annual erosion rates and episodic erosion due to the low costs and easy construction, inspection, and decommissioning.

By analyzing the cost of current erosion control measures in Alaska, in regions with and without permafrost, we show that the unit cost of erosion control structures has been escalating over the past 40 years (approximately 10% increase in cost per year). We also found that both the median unit cost and median total cost are higher for measures implemented in permafrost regions than those in non-permafrost regions; both permafrost and non-permafrost case studies in this cost analysis are located within the northern high-latitude regions.

The potential erosion control measures and promising techniques synthesized in this study include geosynthetics, the static bay beach concept, insulation systems, and microbial applications. The potential of these emerging measures and techniques for full-scale application on northern high-latitude coasts are discussed after reviewing the available research studies on their efficacy and performances under the high-latitude conditions, especially under the existence of sea ice and permafrost. Integrations of these potential measures and techniques with conventional measures are recommended and possible combinations are presented. We also propose to use a combined assessment (i.e. life cycle cost analysis and life cycle assessment) that incorporates both environmental and socio-economic impacts for optimal measure selections. This study shows that a wide knowledge gap still exists in the field application of the new measures and techniques in northern high-latitude regions even though some of them have already been widely implemented in mid- to low-latitude regions. Through the synthesis of the research gaps and challenges, future research can be directed towards upscaling of the emerging erosion control measures and techniques in northern high-latitude coastal regions.

### Acknowledgments

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## Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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