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Article

Geotechnical Measurements for the Investigation and Assessment of Arctic Coastal Erosion—A Review and Outlook

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Abstract: Geotechnical data are increasingly utilized to aid investigations of coastal erosion and the development of coastal morphological models; however, measurement techniques are still challenged by environmental conditions and accessibility in coastal areas, and particularly, by nearshore conditions. These challenges are exacerbated for Arctic coastal environments. This article reviews existing and emerging data collection methods in the context of geotechnical investigations of Arctic coastal erosion and nearshore change. Specifically, the use of cone penetration testing (CPT), which can provide key data for the mapping of soil and ice layers as well as for the assessment of slope and block failures, and the use of free-fall penetrometers (FFPs) for rapid mapping of seabed surface conditions, are discussed. Because of limitations in the spatial coverage and number of available in situ point measurements by penetrometers, data fusion with geophysical and remotely sensed data is considered. Offshore and nearshore, the combination of acoustic surveying with geotechnical testing can optimize large-scale seabed characterization, while onshore most recent developments in satellite-based and unmanned-aerial-vehicle-based data collection offer new opportunities to enhance spatial coverage and collect information on bathymetry and topography, amongst others. Emphasis is given to easily deployable and rugged techniques and strategies that can offer near-term opportunities to fill current gaps in data availability. This review suggests that data fusion of geotechnical in situ testing, using CPT to provide soil information at deeper depths and even in the presence of ice and using FFPs to offer rapid and large-coverage geotechnical testing of surface sediments (i.e., in the upper tens of centimeters to meters of sediment depth), combined with acoustic seabed surveying and emerging remote sensing tools, has the potential to provide essential data to improve the prediction of Arctic coastal erosion, particularly where climate-driven changes in soil conditions may bias the use of historic observations of erosion for future prediction.

Keywords: Arctic coastal erosion; geotechnical site characterization; multi-disciplinary measuring strategies

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1. Introduction

Coastal and riparian erosion represent immediate and increasing risks to many Arctic communities, particularly because much infrastructure is aligned or connected to rivers and the sea as well as impacted by climate change [1–3]. Coastal erosion in high-latitude environments is particularly complex, and drivers of erosion vary for different locations due to variations in soil ice content and the nature of freeze–thaw processes, to name just one example of varying environmental conditions affecting the soil. Furthermore, many current permafrost regions are subject to thawing and degradation in response to climate change, and thus, past observations may not enable confident future predictions without a detailed understanding of the soil conditions.

Are [4] suggested that coastal erosion of permafrost regions can be accelerated by 3–4 times due to thermal abrasion. Thermal abrasion refers to an increase in erosive energy from seawater temperature over mechanical wave energy acting on the sediments alone [4]. Others suggested that thermal impacts do not increase the volume of possibly erodible material, because erosion rates still mostly depend on waves and currents; however, thermal impacts make sediment available for transport by waves and currents, and those impacts will accelerate by about 1.5 times in the second half of the 21st century [5]. Sinitsyn et al. [6] observed variations in coastal erosion associated with varying impacts from mechanical wave action, thermal abrasion, thermal denudation (i.e., thawing of permafrost from air temperature and solar radiation), or a combination of those in the Varandey region of the Barents Sea. Thermal denudation can even represent a controlling process for shoreline erosion, as has been shown in the Gulf of Kruzenstern [7] or along the Itkillik River, Alaska [8]. It follows that Arctic coastal erosion shares similarities with erosion processes in lower latitudes, such as the importance of storms, waves, and flooding, but is also affected by cold-region-specific issues such as ice dynamics, permafrost, and thermal processes such as thermal abrasion and thermal denudation. Many of these processes are subject to change and even to intensification and acceleration due to climate change [9].

The importance of local geology, soil conditions, changes in soil conditions from thaw as well as freeze–thaw cycles, and soil and geomorphological alterations through human activities for Arctic coastal erosion have also been recognized [10]. Geotechnical properties of local soils may affect coastal and riverbank erosion in different ways. Large erosion events are often related to slope failures and bluff erosion. Oversteepening of the slopes from toe erosion, water level variations, and groundwater dynamics, or changes in soil strength from permafrost thaw, variations in saturation, and changes in vegetation, can lead to large mass-erosion events. Retrogressive thaw mud slumps represent an example of how permafrost thaw causes frozen and thus strong soils to transition to soft and weak soils that can sustain only less steep slopes and lower hydraulic shear stresses than the frozen version of the same material [11]. Geotechnical properties and failures not only govern large mass-erosion events, but also affect general erodibility of soils [12]. For coarse-grained sediments, friction angles and relative density (i.e., the particle packing regarding its loosest or densest configuration) affect the critical shear stress needed to mobilize sediments [13]. The erodibility of fine-grained sediments is governed by the cohesion of the specific materials as well as the state of consolidation [14,15]. Sediment mixtures often do not fit traditional models and expressions of critical shear stress and erodibility, and require testing to reveal their actual critical shear stress and erodibility. Recent studies highlighted that fine sediment contents of as little as 35% and less for layered samples can shift the soil steady-state strength, and change the soil's response to stressors significantly [16]. In high-latitude marine environments, coarse-sand–mud mixtures or gravelly mud represent complex seabed conditions with substantial variability in strength and erodibility [17]. Here, the question of selective sediment transport and associated re-distribution of sediments geospatially may become important. Additionally, Are [4] highlighted that thermal abrasion often exposes unconsolidated fine-grained materials that are significantly more erodible than their normally or overconsolidated counterparts [14]. Thus, standard values of erodibility based on grain size and soil type may not apply due to differences in the state of consolidation.

Key geotechnical properties relevant to assessing the likelihood of erosion from mechanical abrasion (i.e., waves), thermal abrasion, or slope and block failures can include, for coarse-grained sediments, relative density and void ratios (i.e., packing state), saturation (ice and/or water), friction angles, and apparent cohesion from partial saturation or from the presence of ice. For fine-grained sediments, key geotechnical properties are similar, including bulk density and void ratios, water and ice content, Atterberg limits (plasticity index, plastic limit, liquid limit), undrained shear strength, and cohesion. These properties can inform the assessment of slope and block failures [18,19], as well as the prediction of critical shear stress and erodibility [12].

Sediment type distributions as well as geotechnical properties of seabed and coastal sediments are complex in the Arctic [17]. Geotechnical properties are affected by coastal geomorphodynamics [20], representing a feedback loop between geotechnical sediment properties and hydrodynamically driven geomorphodynamics [21]. In Arctic and sub-Arctic environments, geotechnical properties may vary even more widely and in a more complex manner from changes in cohesion from freeze–thaw cycles or ice content [22,23]. Additionally, break up of land-fast and seabed-fast ice and associated possibilities of sediment relocation and reworking; seabed–sea ice interaction such as seabed gouging by ice and ice floe–keel scouring; mass sediment deposits from retrogressive thaw mud slumps and bluff erosion; and changes in the coastal zone control offshore permafrost characteristics and the associated geotechnical properties of offshore seabed sediments [24] (Figure 1). While these Arctic processes as well as general processes of sediment dynamics have been subject to many studies, they have rarely been considered holistically and in the context of how they shape the geotechnical properties and seabed soil behavior in the Arctic. Similarly, while it is well-acknowledged that these processes are affected by and may intensify in the context of climate change and rapidly rising temperatures in the Arctic, researchers are still struggling to integrate all or even a number of these processes in multi-processes and hazards models to predict Arctic coastal evolution with climate change, and even more so, to integrate geotechnical concepts in such models. A consequence is that current Arctic coastal erosion risk assessment regarding the consideration of soil properties is based on site-specific shoreline observations, limited permafrost monitoring, and often coarse-resolution soil maps, or require costly site characterization often in excess of project budgets.

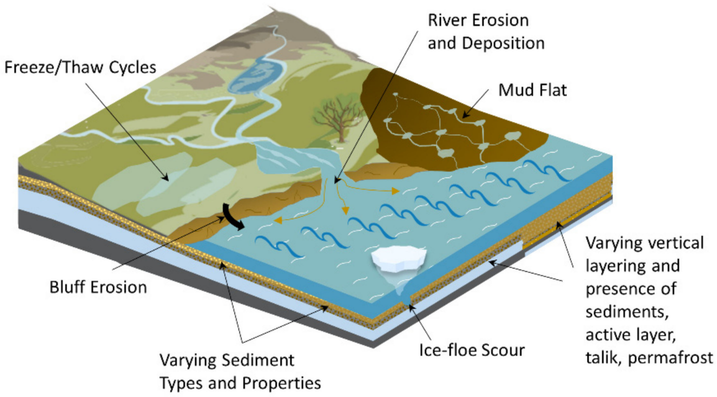

Figure 1. Simplified conceptual sketch of some processes affecting geotechnical Arctic coastal and nearshore sediment properties.

The purpose of this article is to review the current state of geotechnical methods and data availability in Arctic coastal environments relevant for erosion assessment, and to offer perspectives of novel data collection strategies to enhance current geotechnical data availability.

2. Geotechnical Data Collection in Arctic Coastal Environments

The search for public geotechnical data from Arctic coastal environments led to limited results. Hoque and Pollard [25] examined the role of geotechnical properties with emphasis on compressive strength, tensile strength, and shear strength of soil–ice mixtures in the context of block failures and Arctic coastal erosion. They highlighted the lack of available geotechnical data of soil–ice mixtures in the permafrost literature as a restricting factor in their block failure model. The relationships and recommended geotechnical parameters presented were based on controlled laboratory testing of ice–soil mixtures [25]. Similarly, Brouchkov [26] examined the behavior of frozen saline Arctic coast soils through laboratory testing, adding the complexity of soil behavior response to changes in salinity.

Cone Penetration Testing (CPT) represents a key geotechnical site investigation method in coastal and offshore environments, and has also been proposed for Arctic site investigation despite possible challenges regarding sensor robustness in frozen geomaterials [27–29]. CPT typically measures tip resistance, sleeve friction, and (in recent studies) pore pressure against a cone that is driven vertically into the ground with rods of the same diameter and with a penetration rate of 2 cm/s [30]. The following parameters are typically derived from CPT: undrained shear strength for fine-grained soils, and relative density and friction angles for coarse-grained soils. Relationships to the rigidity index or unit weight have also been demonstrated, amongst other correlations [31,32]. Often, CPT is also used to classify the soil within soil behavior type groups relating the results to sensitivity, the overconsolidation ratio, and other properties [33]. Finally, pore pressure dissipation tests carried out using CPT can be used to estimate the coefficient of consolidation [30]. Initial Arctic CPT deployments were carried out by researchers such as Blouin et al. [29] and Baeverfjord et al. [34] in combination with the deployment of thermistors, soil sampling, and drilling in coastal permafrost and frozen soils. Blouin et al. demonstrated that seabed sediment properties down to 14 m below the seabed, including ice-bonded material, were profiled and mapped using CPT, while measuring soil temperature simultaneously [29]. Baeverfjord et al. acknowledged the challenges associated with frozen soils, and the need for, in some cases, modified instrumentation, but they also highlighted the importance of geotechnical data to predict Arctic coastal erosion rates and design sustainable infrastructure [34]. Bashaw et al. [35] assembled a data set including 600 boreholes and 75 CPTs from the Foggy Island Bay area in the Alaskan Beaufort Sea in an effort to characterize geotechnical soil and permafrost for the design of a buried pipeline. Ladanyi, in multiple studies, investigated the merit of CPT for Arctic soil, and more specifically frozen soil characterization. They highlighted that CPT succeeded in assessing the ice bonding in offshore sediments, deriving creep parameters, pile design loads, and strength profiling [36,37]. Isaev demonstrated the use of CPT in varying frozen soils, showing typical CPT tip resistances of up to 30 MPa and suggesting standardized testing procedures [38,39]. In summary, CPT represents a standard and often top choice methodology to profile sediment strength onshore, offshore, and even in frozen soils. It is a powerful tool for geotechnical soil characterization to depths on the order of meters and beyond and in the presence of ice. For the investigation in the presence of ice, it provides stratigraphy with depth and strength properties of those strata including the frozen layers. The derived properties assist with assessing the likelihood and geometry of slope and block failures, and thus, CPT has great potential for the prediction of large-volume erosion events [34]. It also enables the development of a full model of the sub-strata that can be correlated to soil temperature profiles [29,34]. However, the literature review also suggested that actual CPT deployments in the Arctic, and particularly in Arctic coastal environments, are still limited, and then, typically related to large infrastructure investments or to resource exploration and exploitation. Despite the fact that Baeverfjord et al. specifically mentioned the value of CPT data for soil assessment in permafrost regions in the context of Arctic coastal erosion prediction [34], the authors of this study did not identify other studies in which CPT was deployed for this purpose. The reasons for this are likely associated with costs. If the penetration of frozen soils is desired, significant resisting forces are acting on the CPT (up to 30 MPa according to [38]). This calls for a significant reaction frame infrastructure to push the CPT, availability of replacement materials, and an experienced operator, all leading to significant costs, which may be suspected as a main reason for limited application for Arctic coastal erosion. Furthermore, it has yet to be quantified how much CPT data would affect risk assessment for specific sites over having no such data available and using estimated parameters.

Free-fall penetrometers (FFPs) have gained attention due to offering strength profiling of seabed sediments in a rapid and cost-effective manner [40,41]. Deployment and data analysis standards have been proposed for FFPs with CPT-like piezocone sensor suites [42], while other designs, often based on accelerometers, have been introduced for specific environmental challenges [43]. FFPs strive to correlate to similar geotechnical properties as CPT. However, most commonly undrained shear strength is derived for fine-grained soils [44,45]. Recently, FFPs have been used to monitor relative density and friction angles in sandy nearshore environments [46], and to estimate the coefficient of consolidation of fine-grained nearshore and estuarine sediments [47]. FFPs offer detailed insights into seabed layering and have been suggested for the monitoring of changes in the mobile sediment layer in areas of active sediment dynamics [48,49]. Portable FFPs have been introduced for deployments in the intertidal and nearshore zone, offering a seamless collection of geotechnical data across different coastal zones [43,50] and have also been successfully applied in coastal Arctic and sub-Arctic environments. During the YUKON14 expedition to Herschel Island, Yukon Territory, Canada, a portable FFP was deployed at more than 200 sites in the nearshore zone of Herschel Island in water depths of ~1–20 m [17,51]. Deployment locations included sheltered areas, such as Pauline Cove, within the vicinity of retrogressive thaw mud slumps, and the workboat passage between the island and the mainland, as well as towards a deeper basin in Thetis Bay and exposed sites such as Collinson Head [17,51]. This was feasible due to a portable FFP that does not require any significant infrastructure and was deployed from agile rigid-hull inflatable vessels (Figure 2). A major disadvantage of FFPs is that they are limited in penetration depth, depending on the device weight, impact velocity, geometry, and sediment stiffness. FFPs have demonstrated penetration depths on the order of several meters, with less penetration depth in hard coarse-grained sediments and larger penetration depths in soft fine-grained sediments [42]. Small-scale, portable FFPs can be limited to penetration depths of 1–2 m in soft sediments and of 0.2–0.3 m when impacting hard seabed sediments [17,43]. During YUKON14, the portable FFP achieved penetration depths of up to 1.2 m [17,51]. It resolved vertical layering, likely associated with different sediment erosion and deposition events, and mapped changes in surficial seabed strength which were related to local sediment dynamics, mass sediment inputs from retrogressive thaw mud slumps, and the presence of underconsolidated sediments which may be related to the presence of gas– or seabed–ice dynamics [17,51,52]. The portable FFP data were correlated to the median grain size of grab samples and to side-scan sonar backscatter intensity seabed surface mapping [53]. The same device was also most recently applied during an Arctic expedition to Harrison Bay, Alaska [53]. Here, 656 FFP deployments were carried out from a mid-size vessel. Significant variations in sediment strength were associated with the prevailing sediment grain size, but also spatially associated with notable changes in bathymetry likely from ice floe–keel scour. Data processing is still ongoing, including a correlation to local bathymetry, acoustic backscatter intensity, and laboratory testing of sediment erodibility. A goal of this study was to utilize the geotechnical data to inform a short-timescale geomorphodynamical model of the Arctic continental shelf in the area, building on recent work to characterize millennial-scale shelf evolution [54].

Figure 2. Portable free-fall penetrometer *BlueDrop* during YUKON14 deployments.

FFPs may offer a more feasible and cost-effective option for geotechnical measurements of seabed surface sediments; however, they are clearly restricted in penetration depth and do not enable strength profiling of permafrost soils. Therefore, FFPs would be most useful to derive geotechnical parameters for the assessment of erosion from mechanical abrasion and through the assessment of critical shear stresses for initiation of motion and erodibility. Furthermore, they may be useful to identify near-surface ice and sediment-laden ice blocks fastened to the seabed.

Hoque and Pollard [25] presented a model of Arctic coastal cliff failure and highlighted the importance of strength parameters of frozen and unfrozen soils, but these authors used established relationships from laboratory testing. Lantuit et al. [55] used a frost probe and a hand vane shear device to measure median active-layer depth and shear strength within retrogressive thaw mud slumps composed of very fine grained sediments, an active layer thickness on the order of tens of centimeters, and very low sediment strengths (<1 kPa). The same authors applied a similar methodology during the YUKON14 expedition, and the more recent availability of digital field vane shear devices offers improved performance for this approach. Thus, it has been shown that hand-held field vane shear devices can offer data from otherwise hardly accessible locations such as cliffs and retrogressive thaw mud slumps. Hand-held vane shear devices are restricted to measuring shear strength near the surface, but could enable deeper measurements after excavation of the surface material.

3. Geophysical and Remote Sensing Opportunities in Arctic Environments

Numerical models to simulate erosion in any coastal environments and coastline evolution require information on coastal topography and bathymetry of the littoral cell. This also applies to models specific to Arctic environments. For example, Arctic Beach 1.0 requires historic coastal retreat values (or at least one starting value) and a nearshore bathymetry [56]. Shoreline retreat rates can be determined from historic or current aerial imagery, aerial light distance and ranging (lidar), satellite imagery, historic maps, and local knowledge and environmental observations [2,57–59]. Bathymetry is most commonly determined from multi-beam echo sounders (MBESs) [59,60]. The backscatter intensity from MBESs or side-scan sonar can also be used for mapping of surficial seabed conditions, specifically when correlated to sediment samples and geotechnical testing [17]. MBESs have furthermore been applied to submarine slope characterization as well as ecological investigations in the Arctic [61,62]. Most recent developments of lidar may offer even more efficient solutions to combine onshore topography and bathymetry measurements by adding a bathymetric lidar. Tysiac [63] demonstrated the use of bathymetric lidar for coastal zone assessment and combined it with geotechnical measurements. A similar approach could increase efficiency and offer seamless onshore topography to offshore bathymetry data fused with geotechnical data. However, it should be noted that bathymetric lidar is restricted by water turbidity, and thus, may not be a reliable tool in the presence of suspended sediment plumes or generally high abundance of suspended matter.

Chirp sonar and sub-bottom profiling have been applied in a number of Arctic locations and offer insights into seabed stratigraphy. This has enabled the reconstruction and quantification of erosion and deposition events by correlation of different strata [64]. Furthermore, Shakova et al. [65] demonstrated the use of chirp sonar in combination with side-scan sonar imagery and seabed borings to detect and quantify permafrost degradation and gas migration pathways in submerged coastal Arctic environments. Chirp sonar has also been correlated to geotechnical in situ testing in addition to sediment core characterization, and thus, offers a powerful tool to interpolate and extrapolate from geotechnical point measurements in addition to offering deeper penetration depths and mapping of gas, which can have significant impacts on Arctic seabed sediments [66].

Remote sensing opportunities are particularly attractive for Arctic coastal environments because they may improve the number of data collected in remote regions which are difficult to access. Remote sensing using unmanned aerial vehicles (UAVs) is becoming increasingly popular due to its broad application potential. Small UAVs (sUAVs, generally considered less than 23 kg in operational mass) are inexpensive, easy to operate, capable of operating at very low altitudes and/or velocities, and can overcome many of the shortcomings present in terrestrial optic remote sensing techniques including problems with cloud cover, which are common in the Arctic [67]. Perhaps the most intriguing advantage of small UAVs is their ability to bring the sensor as close to the potential target as needed, thus providing the potential for very high image resolutions and avoidance of obstacles [68]. Most commercial off-the-shelf sUAVs today can readily collect imagery from sites up to two kilometers from the UAV operator if sufficient transmission signal is present. Advances in UAV photogrammetry and Structure from Motion (SfM), including the use of UAV-mounted Real-Time Kinematic (RTK) GPS, have greatly impacted the usability of UAVs in monitoring large areas by decreasing the collection time, performing targeted and multi-tiered imaging, and increasing the accuracy of the 3D reconstruction [69,70]. For example, Figure 3 presents a coastal slope south of Anchorage that was impacted by localized landslides (circled in yellow) following the November M7.0 2018 earthquake [71]. Such advances in UAV-based remote sensing in the Arctic have allowed observations of centimeter-scale changes in glacial ice [71–73], snowpack [74], and permafrost degradation [75]. Lamster et al. [73] demonstrated the capabilities of UAV photogrammetry in monitoring multi-year changes in an Arctic glacier from 2019 to 2021. From the data they collected, they were able to determine elevation change, geodetic MB, and surface velocities [73]. Lou et al. [74] used thermal infrared imagery to estimate the spatial distribution of ground surface temperatures of permafrost. They used this data to determine the effects of the surrounding infrastructure on the permafrost. Van de Sluijs et al. [75] used UAV surveys to monitor permafrost thaw subsidence impacts on or close to road infrastructure. A combination of Lamster et al.'s, Luo et al.'s, and Van de Sluijs et al.'s work could be used to monitor changes and the rate of change in snowpack, erosion, sea ice extent, and permafrost degradation surrounding Arctic communities' built environment. Furthermore, the demonstrated potential of UAVs to autonomously detect anomalies or features of interest and perform autonomous sequential monitoring of areas of interest could provide significant promise for UAVs in monitoring the progression of coastal and riverine erosion in the Arctic [76,77].

Figure 3. UAV-based 3D SfM reconstruction of an Arctic coastal slope near Anchorage that was impacted by an earthquake and landslides in 2018 (localized landslides are circled in yellow).

Challenges of operating sUAVs in the Arctic remain and must be overcome if these sensor platforms are to achieve their full potential. Battery-operated platforms have significant limitations when operating in extreme environments (i.e., temperatures greater than 43 degrees Celsius or less than −5 degrees Celsius), locations with inclement weather, and/or remote locations without a portable power source to recharge batteries in the field. Currently fixed-wing UAVs have much greater endurance potential, though their limitations in maneuverability and sensor orientation limit the type and quality of data that can be collected [78]. Gasoline-powered single- or multi-rotor UAVs have the potential to overcome many of the limitations presented by battery-powered rotor UAVs, though such platforms are not yet readily available commercially. Current sensors used with sUAVs are generally optical and limited by the line of sight, which poses a challenge to collecting geotechnical data from soils in the sub-surface. While the use of other sensors, such as interferometric synthetic aperture radar (inSAR) or ground-penetrating radar, offers the potential to measure some useful soil properties below the ground surface, most sensors are best-suited to measuring conditions directly on the ground surface. Interestingly, some novel adaptions to the traditional use cases of UAVs are opening the door to collecting more geotechnical data from below the ground surface. For example, Greenwood et al. [79] used UAVs to drop weights as an energy source for multi-channel analysis of surface waves for shear wave velocity profiling in the sub-surface.

The most recent advances in satellite-based sensing also enable novel opportunities. These advancements are related to sensor types and quality, pixel size, and availability of imagery and satellite return periods. Topography [80], vegetation mapping [81], soil type mapping [82], and flood and ice extent mapping are a few examples for which satellite-based data have been heavily used [83,84]. Recently, synthetic aperture radar (SAR) imagery has also been utilized to track ice dynamics [85], and multi-spectral and SAR imagery have been applied to estimate soil moisture contents in coastal environments [86]. Hyperspectral imagery from satellites, manned aircraft, and UAVs has allowed for the estimation of surficial sand density [87]. Regarding geotechnical characterization of coastal environments, differently derived remotely obtained soil and environmental properties can be “fused” towards a more holistic soil characterization of these environments [88]. For example, the knowledge of surficial soil moisture (from satellite or UAV data) at different times under different environmental conditions (rainfall, flood stage, etc.) in combination with knowledge of topography and general soil type (from satellite, UAV, or historic data) can represent a strong initial data base For the development of models to assess riverbank or shoreline slope stability in the absence of geotechnical data from physical in situ testing and sampling. This can be further strengthened by fusion with traditional data collection methods, which could also be more strategically deployed based on initial remotely sensed data (see Section 4.1). As another example, deriving the density and friction angles of coarse-grained sediments, as shown by [87,89], could also improve the assessment of erodibility of sandy shorelines and may assist with the identification of possible erosion hotspots which require further investigation. However, satellite- or UAV-based remote sensing has so far been rarely used to derive geotechnically relevant information in Arctic environments, and this may also be further complicated by soil transition between frozen and thawed and permafrost [90,91]. More research is needed to fully assess the potential and most valuable applications of these methods.

4. Integrated Data Collection Strategies

4.1. Geotechnical and Geophysical Soil Characterization

Combined geotechnical and geophysical data collection and analysis is common for many engineering applications as well as for the investigation of natural processes and natural hazards [66,92–94]. In the past, this has often been limited to spatial alignments and interpolations in which vertical strata and/or spatial variations are derived from the geophysical data, and are related to geotechnical data from in situ testing and core sample testing at specific locations. Data fusion between geotechnical and geophysical data will likely be moved into a more quantitative fusion using the most recent efforts of connecting geotechnical seabed properties and geoacoustical seabed properties through geoacoustic theory and empirical correlations [95,96]. So far, this effort has been hampered by data availability and quality, as well as by differences in resolution and computing capabilities.

Machine learning approaches, increased accessibility to quality data collection equipment, and thus, data sets, promise continuing advances in this matter [66]. This is of specific relevance for Arctic data collection, as the fusion of geoacoustic and geotechnical data will enable the reduction in costly and difficult physical data collections due to a reliable and accurate correlation to geoacoustic data that is easier and quicker to obtain.

Similar arguments can be made for emerged coastal sediments where geotechnical site characterization can benefit from remotely sensed data. This also paves the way for larger spatial and temporal coverage, including data collection in hardly accessible locations. For example, it can be envisioned that initial physical geotechnical site characterization is being applied to calibrate geoacoustic and remotely sensed data products so that repeat surveys can rely on non-invasive testing and remotely sensed data alone. Simplification through reduction in physical data collection methods also has the potential to increase the role of local communities and stakeholders in data collection and monitoring efforts by simplifying training needs, increasing ruggedness, and simplifying operations of instrumentations (e.g., considering the use of handheld vane shear devices, free-fall penetrometers, and UAV data collection). Figure 4 offers an overview of different data collection methods for comprehensive and optimized data collection of geotechnical data in Arctic coastal environments.

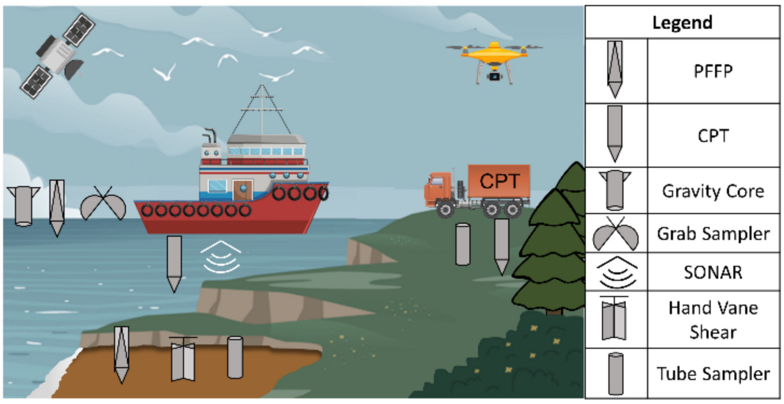

Figure 4. Conceptual sketch of combined data collection strategies for optimized coastal geotechnical site characterization in Arctic environments.

4.2. Integration of Geotechnical Information for Use in Coastal Geomorphological Models and in the Prediction of Coastal Erosion

Arctic coastal systems are a key target for improved morphologic modeling of coastal retreat, nearshore processes, and continental shelf changes, all of which are regulated by soil and sediment erodibility. Morphologic modeling directly serves the understanding and prediction of ongoing and future shoreline changes, as well as changes in nearshore and offshore bathymetry relevant for applications such as navigation and accessibility, but also for predicting future changes in coastal wave impacts. Onshore, recent and ongoing work has been addressing rates of bluff retreat, which is complicated by the presence of massive ground ice (permafrost wedges) and variable importance of mechanical erosion by waves (niching) versus thermal erosion by warm seawater [97–100]. A lack of information on erodibility of these permafrost soils has made this type of modeling challenging [101]. Furthermore, geotechnical data from, e.g., CPT testing can provide accurate soil information for modeling block failure, identification of weak layers, and predicting slope failures [25,34].

Once sediment is released from coastal bluffs (or delivered by rivers), it becomes an important part of the nearshore sediment budget and also supplies mass (and associated nutrients) to the continental shelf [97,101–105]. In the nearshore, geotechnical properties of the seafloor depend partly on the presence of sub-sea permafrost which has not yet degraded following coastal retreat [65,106,107] and exhibits a seasonal active layer, much like terrestrial permafrost [108]. The nearshore also experiences disturbance by landfast ice and/or bottomfast ice [109,110], formation of anchor ice [111], and strudel scour [112], processes which can pose erosion hazards for buried pipelines [113]. Farther offshore on the continental shelf, the upper limit of sub-sea permafrost has typically decayed to several meters to tens of meters below the surface [106,114], and is likely less important in considerations of seabed erodibility. However, scouring and disturbance of the seabed by sea ice is zonally important on the shelf. In the stamukhi zone (typically at 20–40 m water depth), drifting pack ice collides with landfast ice and builds pressure ridges with submarine keels, which gouge the seafloor, sometimes to depths of several meters [113,115,116]. These processes likely have a substantial impact on seabed erodibility, but limited work has been carried out to quantify these properties.

In nearshore zones, significant variations in geotechnical properties of seabed surface sediments occur and are associated with changes in wave action and local sediment dynamics [20,46,49]. These variations affect erodibility [12–15]. Many modern morphological nearshore models consider parameters which describe these properties, but they have rarely been updated or calibrated by actual measurements since geotechnical measurements in nearshore zones have just recently become more feasible [43]. Significant efforts are ongoing to include in situ and even remotely assessed geotechnical parameters in nearshore morphological models. Similarly to above mentioned studies, significant variations in geotechnical properties have been documented in Arctic and sub-Arctic environments [17,117]. Those data have improved the understanding of local sediment dynamics processes, and it can be hypothesized that, similarly as for non-Arctic environments, the consideration of in situ geotechnical properties in Arctic nearshore geomorphologic models would serve the improvement of accuracy and decrease in uncertainty of those models.

Limited research has addressed erodibility of nearshore seafloor sediments derived from bluff erosion and/or riverine sources largely in the context of infrastructure constructed to support industry facilities [118–120]. Much of this work has relied on geophysical methods rather than direct sampling, though a limited number of penetrometer studies have been conducted. Relatively little work has been carried out since then to characterize the geotechnical properties of Arctic nearshore and continental shelf environments. Understanding the erodibility of Arctic shelf sediments, which are uniquely impacted by ice processes (relative to their temperate counterparts), will be critical to future efforts to understand both the modern and historic Holocene evolution of Arctic shelf and coastal environments.

5. Summary

Arctic coastal change in the context of climate change represents a pressing societal issue. Geotechnical information of Arctic coastal and nearshore sediments can contribute to improving the understanding of the governing processes, assessing risks, and developing response and mitigation strategies. Geotechnical data collection is challenging in highly dynamic coastal environments, and particularly in the Arctic. A review of geotechnical and geophysical data collection methods suggested that the use of small-scale and portable devices simplifies geotechnical data collection, while still providing key information, particularly for the investigation of active sediment dynamics. However, coring, drilling, and Cone Penetration Testing may be needed to characterize deeper and/or ice-rich sediments. Furthermore, data fusion with geoacoustic methods for seabed characterization and with remotely sensed data for emerged coastal environments offers pathways for optimization and simplification of data collection, possibly enabling larger spatial coverage, temporal studies, and the increased involvement of local communities and stakeholders in data collection.

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