

Assessing Variations in Sediment Properties and Erodibility in Harrison Bay, Alaska, Using a Portable Free-Fall Penetrometer

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Abstract: Geomechanical data of Arctic nearshore and offshore seabed sediments remain sparse. Two field surveys were conducted in Harrison Bay, Alaska, in the summers of 2021 and 2022. These surveys involved portable free-fall penetrometer (PFFP) deployments, grab sampling, gravity coring, and compressed high-intensity radar pulse sonar for seabed investigation and bathymetric surveying. The goals of this study were to test geomechanical seabed surface sediments in situ using a PFFP, relate those properties to erodibility parameters from a jet erosion test (JET), and demonstrate the potential use of geomechanical seabed mapping to better inform numerical models of shelf morphological evolution in an Arctic environment. After deriving the firmness factor (FF) from the PFFP data, a classification scheme was developed with an $FF = 450 \text{ m}^{-1}$ threshold differentiating cohesive and noncohesive sediments at a threshold fines content of 30%. Strength properties were then calculated for cohesive or noncohesive sediments, respectively. For noncohesive sediments, the packing state in the form of relative density was related to the JET-derived detachment coefficient, k_d , with the critical shear stress being determined via empirical relations. Three categories were assigned for cohesive sediments: an undrained shear strength separator of $s_u = 2 \text{ kPa}$ correlated well with groupings of k_d obtained from JET performed on gravity core samples, and the third category for the least erosive sediments was developed for s_u values greater than 20 kPa. These categories helped explain variability in erodibility and sediment strength across the entire bay and a focused 13 km transect on the inner shelf. Recently deposited sediment from bluff erosion and ice-scoured seabed were both classified in the highest erodibility group, highlighting the usefulness of this classification system for studying morphodynamics in Arctic environments. **DOI:** [10.1061/JCRGEL.CRENG-857](https://doi.org/10.1061/JCRGEL.CRENG-857). This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <https://creativecommons.org/licenses/by/4.0/>.

Introduction

Arctic coastal and nearshore environments are being heavily impacted by climate change. Warming temperatures have led to decreases in seasonal sea ice thickness and extent, leading to a longer open water season and increasingly large seasonal fetch (Overeem et al. 2011; Barnhart et al. 2016; Mioduszewski et al. 2018). Increased temperatures have also led to increases in humidity, precipitation, seasonal river discharge, and permafrost thaw rates (Overeem and Syvitski 2010; Box et al. 2019). Sea ice acts

as a natural protection for Arctic coastlines by reducing wave action. Diminishing sea ice allows for more fetch, which increases the duration and energy of wind-waves attacking the coastline. Shorelines composed of permafrost bluffs are especially susceptible to increased wave energy and water/air temperatures. Through a process called thermal abrasion, waves erode the coastline by imparting mechanical and thermal energy into permafrost bluffs, leading to gravity-driven slumping and block failure (Aré 1988). Exacerbating this issue is thermal denudation, a process by which warming air temperatures increase permafrost thaw and ground ice melt (Lantuit and Pollard 2008; Hoque and Pollard 2009; Günther et al. 2015). The effects of both thermal abrasion and thermal denudation have led to high rates of coastal erosion in the Arctic (Jones et al. 2008; Frederick et al. 2016). Rates of shoreline retreat are expected to increase as the aforementioned drivers of erosion strengthen with climate change, leaving Arctic coastlines and communities more vulnerable over time (Ford et al. 2006; Jones et al. 2009; Nielsen et al. 2022).

A consequence of increases in coastal erosion, river discharge, and permafrost block failure and slumping is an increase in sediment supply to nearshore and continental shelf systems (Rachold et al. 2000). The sediment will then be mobilized, transported, and deposited on or beyond the shelf, but the ultimate fate of freshly introduced sediments in the Arctic Ocean remains uncertain. Will it stay in the nearshore and shallow continental shelf areas, where it could potentially be reworked by waves and currents to rebuild the coastline, or will it be transported off the shelf into deep ocean basins and allow for continued coastal erosion? The presence of pack-ice closer to shore in the winter months promotes offshore transport, while open-water summer months allow for

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more onshore transport and deposition on the inner shelf (MacDonald et al. 2015; Forest et al. 2016). Sediment entrainment in sea ice provides a mechanism for exporting sediment into deep ocean basins (Nürnberg et al. 1994). Additionally, coastal morphology plays an important role in determining transport mechanisms. A study in the Canadian Beaufort Sea found that coastlines backed by bluffs favored offshore-directed sediment transport during storms more than low-lying barrier island systems where overtopping allowed a more onshore-directed component (Héquette et al. 2001). It has also been suggested that decreases in ground-ice and permafrost will increase delta progradation rates and decrease the offshore transport of fluvial sediment (Piliouras et al. 2021). Still, the relationship between sediment dynamics, hydrodynamics, and climate change is a complex interaction that is still under investigation and further complicated by often limited information about detailed seabed sediment properties (Macdonald et al. 2015; Wegner et al. 2015; Osborne and Forest 2016).

Nearshore sediment dynamics are strongly controlled by sediment properties. In Arctic environments, sediment grain size is a controlling but highly variable factor in erosion rates, with coarse-grained (fines content < 50%) deposits having lower erosion rates than fine-grained deposits (fines content > 50%) (Reimnitz et al. 1985). Horizontal and vertical variations in sediment types can result from varying and changing riverine sediment inputs and bluff erosions, along with ice-gouge reworking of seabed sediments (Reimnitz et al. 1977; Barnes et al. 1980; Barnes et al. 1985). Sediment properties, including but not limited to grain size, directly affect erodibility (Shields 1936; Shafii et al. 2016; NASEM 2019). Hence, it follows that high variability in sediment properties would lead to a commensurate degree of variability in the erodibility of these sediments.

Measuring in situ sediment properties, critical shear stress, and erosion rates for surficial seabed sediments would be an important step toward improving the understanding and prediction of sediment dynamics in Arctic nearshore environments. Enhancing the ability to quantify variations in sediment properties and erodibility could improve numerical models of shelf morphology (Malito et al. 2022). However, in situ measurements of seabed sediments in shallow Arctic areas are difficult due to logistics of fieldwork in remote areas, accessibility of and operation in shallow-water, and presence of sea ice preventing thorough vessel surveying for most of the year. Portable free-fall penetrometers (PFFPs) provide a potential solution to these challenges, particularly where only surface sediments are investigated. Lightweight, rugged, and easily deployable from small vessels, PFFPs have been used for rapid seabed characterization, measurement of in situ geotechnical properties, and investigation of sediment transport and mobilization (Akal and Stoll 1995; Stark et al. 2014a; Albatal and Stark 2017; Lucking et al. 2017). Additionally, PFFPs have been used in Arctic nearshore areas for characterization of seabed bearing strength, pore pressure response, and identification of sediment layering (Stark et al. 2015; Stark et al. 2017; Brilli et al. 2022). Relating PFFP measurements to erodibility would make Arctic geomechanical seabed characterization significantly more feasible, and hence increase data availability (Stark et al. 2022).

The goals of this study are to use PFFP measurements in a highly variable Arctic nearshore environment to develop a regional sediment classification model to understand the variability of geomechanical sediment properties, i.e., strength properties and erodibility, and explore the relevance of these measurements in the context of local geomorphodynamics and for numerical modeling of Arctic nearshore and shallow water environments.

Regional Context

Two field surveys were conducted in July/August 2021 and 2022 in Harrison Bay, Alaska, an embayment of the Beaufort Sea, approximately 70 km west of the town of Prudhoe Bay, Alaska (Fig. 1). Harrison Bay is part of the Alaskan Beaufort Shelf, a 600-km long section continental shelf on the northern Alaskan coast of the Arctic Ocean, which has shelf widths of 50–100 km (Norton and Weller 1984). The bay is shallow (water depths < 20–40 m), and it was chosen due to the presence of fluvial sediment input from the Colville River in the south, bluff erosion on the west side of the bay, and a wide variety of mixed sediment types on the seabed both laterally across the bay and vertically in the strata due to diverse sediment inputs and ice-gouging processes reworking the seafloor (Barnes and Reimnitz 1974; Reimnitz et al. 1977; Barnes et al. 1980; Jakobsson et al. 2020). To the east of the bay, the coastline is dominated by sand and gravel barrier islands fronting shallow lagoons. Sea ice covers the area between October and June, with an average yearly thickness of 2.4 m, and landfast ice can range in extent from 1 to 50 km (Norton and Weller 1984; Barnhart et al. 2014). Sea ice acts to shelter the bay from storms, preventing wave generation, and therefore, sediment transport is largely constrained to the open water season in the summer. The shallow water, which enables the deployment of geotechnical sampling equipment from a small vessel, as well as the wide range of geomorphic processes acting across a relatively small area, made this site well-suited for addressing the goals mentioned in the previous section.

Methods

During the survey in July/August 2021, colocated physical sampling and PFFP deployments were conducted at 63 unique sites across Harrison Bay (darker dots, Fig. 1). Samples were collected using a Shipek surface sampler, and 3–10 PFFP deployments were performed at each site. This round of data collection was primarily used for developing a soil characterization model based on PFFP measurements and for laboratory tests to measure minimum and maximum void ratios for the native sand. In the subsequent 2022 survey, eight gravity core samples were collected from sites across the bay in order to perform laboratory jet erosion tests (JET) on local sediments to obtain near in situ erodibility parameters (Fig. 1; Hanson 1991). The gravity core samples were colocated with PFFP deployments (lighter dots indicate both PFFP and gravity core at location), which were used to correlate erodibility parameters with PFFP data. Also in 2022, a 13-km-long transect line was surveyed on the west side of Harrison Bay, with PFFP deployments approximately every 50 m, totaling 160 deployments [Fig. 1(c)]. These data, along with multibeam echosounder bathymetry (MBES) data [Fig. 1(d)], were used to assess the importance of smaller-scale variations in sediment properties and erodibility.

PFFP Data Analysis

The PFFP *blueDrop* was used during the field surveys. It measures 63.1 cm in length and 8.75 cm in diameter, has a mass of 7.71 kg, and has a streamlined body shape (Fig. 2). The probe is equipped with five vertical accelerometers ranging from ± 2 to $\pm 250g$, and two $\pm 55g$ horizontal tilt accelerometers, where g is the gravitational acceleration.

All accelerometers record continuously at 2 kHz. The device can be deployed from a range of vessels. It is secured with a rope attached to the tail section (Fig. 2), free-falls through the

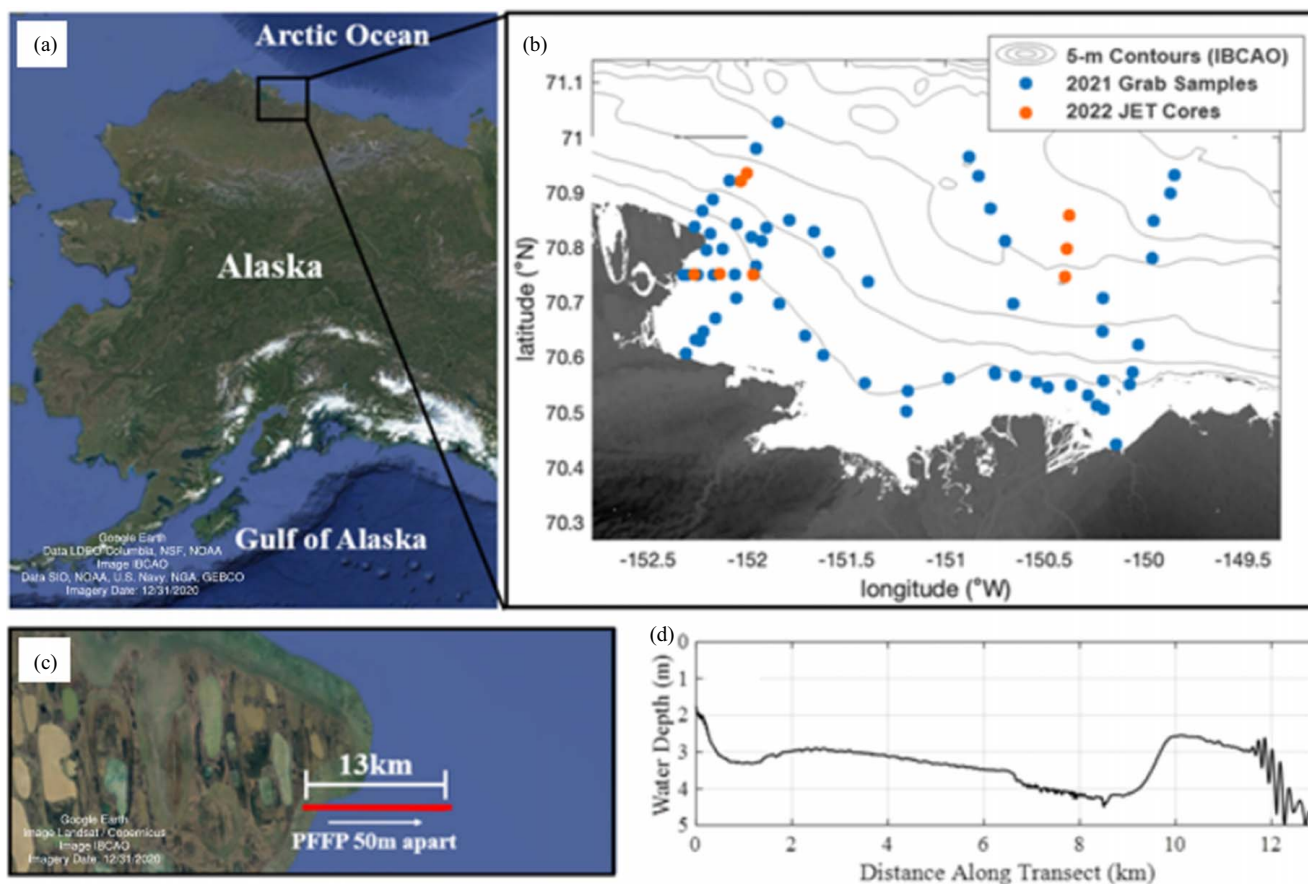


Fig. 1. (a) Google Earth satellite image Harrison Bay, Alaska (N70°14'54.79" W149°41'42.64") (image © Google, Data LDEO Columbia, NSF, NOAA, Image IBCAO, Data SIO, NOAA, U.S. Navy, NGA, GEBCO); (b) layout of physical sampling and PFFP locations from 2021 (darker dots), gravity core locations from 2022 (lighter dots); (c) 13 km line indicates location of linear transect with high-density PFFP deployments from 2022 (image © Google, Image Landsat/Copernicus, Image IBCAO); and (d) transect bathymetry from (c).

water column, impacts the seabed, and is brought to a stop by the resistance of the sediment. Ease of deployment, self-contained recording over a wide range of accelerations, and less than 1-cm resolution in the vertical sediment profile make this tool ideal for rapid

and spatially extensive geotechnical site investigations (Stark et al. 2014b; Albatal and Stark 2017).

The acceleration record from impact with the seabed until the soil resistance brings the probe to a stop can be single and double integrated with respect to time to give profiles of velocity and penetration depth, respectively. Typically, stiffer soils will elicit a stronger deceleration response and softer soils will have a weaker response, reflected in the magnitude of the maximum deceleration recorded by the probe ($a_{\max}$). However, the measured soil strength from PFFP deployments is highly dependent on the rate of strain experienced by the soil, or the impact velocity (v_i) in the case of the PFFP (Dayal and Allen 1973; Dayal et al. 1975). This strain rate dependence means that $a_{\max}$ is dependent on v_i and the soil strength properties. Mulukutla et al. (2011) proposed the firmness factor (FF) as an attempt to normalize the deceleration record using the impact velocity to give a velocity-independent metric proxy of soil stiffness using the raw PFFP data, which can be used for sediment classification and rapid site characterization (Albatal and Stark 2017). The firmness factor (m^{-1}) is given by Eq. (1) and it was used in this study for the purpose of differentiating cohesive and noncohesive sediments

$$FF = \frac{a_{\max}}{v_i g t_p} \quad (1)$$

where t_p = penetration time from impact until stop; and g = gravitational acceleration. Once sediments were classified as cohesive (>30% fines content) or noncohesive (<30% fines content), the



Fig. 2. PFFP, blueDrop, in use during the field survey in Harrison Bay. (Image by Nina Stark.)

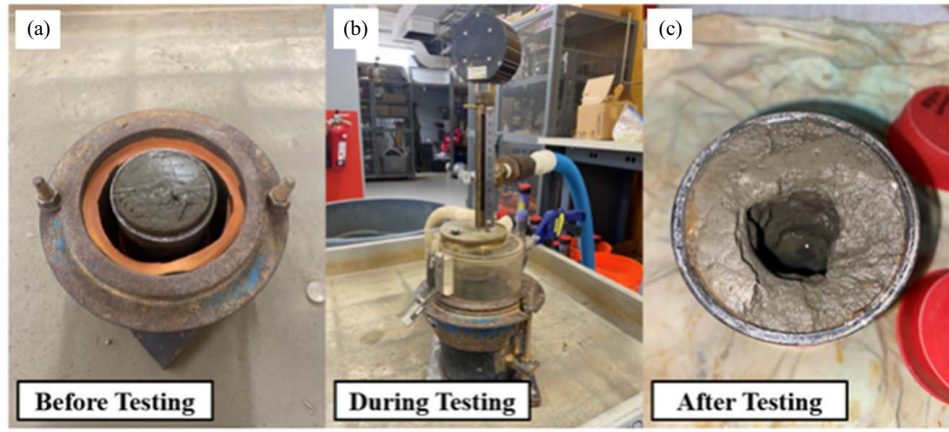


Fig. 3. (a) Sample prepared for testing; (b) mini-JET with sample inside; and (c) sample after testing showing scour hole.

geotechnical properties were characterized following a methodology similar to that proposed by Jaber and Stark (2023). For noncohesive sediments, this means derivation of the relative density (D_r), and for cohesive sediments, the undrained shear strength (s_u) is derived. These properties were then used to define relationships between sediment properties and erodibility parameters.

For coarse-grained (noncohesive) sediments, the acceleration record has been tied to the packing state in the form of D_r . It should be noted that packing state can also be described by void ratio (e), porosity (n), and bulk density (ρ_b). Albatal et al. (2020) performed laboratory tests on a medium quartz sand by dropping a PFFP into a sediment bed over a range of fixed D_r and developed an empirical estimate of D_r (as a %) using only $a_{\max}$ (in g) from the PFFP as follows [Eq. (2)]:

$$D_r = -14.66 \times 10^{-3}(a_{\max}) + 2.66(a_{\max}) - 25.17 \quad (2)$$

While this equation has not been validated for Arctic sands specifically, grain sizes and mineralogy are generally in a similar range, and thus, the equation is assumed to be applicable. Validation is difficult since it requires the retrieval of undisturbed sand samples, or reconstitution of a large volume sample for controlled laboratory tests. Neither undisturbed sampling nor reconstituting was possible due to lack of available sand sample volume, and unavoidable disturbance of samples when retrieved by a grab sampler. Therefore, the results should be considered a best estimate of magnitude.

For cohesive sediments, the determination of s_u requires first determining the bearing strength. Estimating bearing strength from the PFFP applies Newton's second law to the acceleration profile to convert the deceleration response to a sediment resistance force. This sediment resistance force is then divided by the loaded area to give a dynamic bearing capacity (q_{dyn}). This measure is likewise influenced by the aforementioned strain-rate effects. The term q_{dyn} is then normalized toward a tip resistance value in line with the strain rate of a standard cone penetration test, i.e., at 2 cm/s (Stoll et al. 2007; Chow et al. 2017; White et al. 2018), by dividing q_{dyn} by a strain rate correction factor (f_{sr}), given by

$$q_{\text{sb}} = \frac{q_{\text{dyn}}}{f_{sr}} \quad (3)$$

where q_{sb} = quasi-static bearing capacity normalized to a strain rate of 2 cm/s. There are multiple formulations for f_{sr} , the most common being the logarithmic form (Peck 1962; Mitchell 1964) and the power law (Randolph 2004). For this study, the power law was used as suggested for free-fall penetrometer interpretation

in cohesive sediments, as follows (Chow et al. 2017; Jaber and Stark 2023):

$$f_{sr} = \left(\frac{v_{\text{dyn}}}{v_{\text{ref}}} \right)^{\beta} \quad (4)$$

where v_{dyn} = nonlinear dynamic velocity profile; v_{ref} = reference velocity; and β = soil-type-dependent strain-rate factor. The term β was assumed to be 0.035–0.085, with the average value of 0.05 providing the best fit for this study (Randolph and Hope 2004; Chow et al. 2017; Jaber and Stark 2023). Once q_{sb} is determined via Eq. (4), s_u can be calculated as follows:

$$s_u = \frac{q_{\text{sb}}}{N_{kt}} \quad (5)$$

where N_{kt} = cone factor. The term N_{kt} was assigned a value of 10 for this study (Lunne et al. 2002; Robertson and Cabal 2010; Mayne and Peuchen 2018; Jaber and Stark 2023).

Jet Erosion Test

Erodibility parameters were determined in the laboratory using a mini-JET device and setup at North Carolina State University. The JET was originally developed for characterizing erodibility of cohesive soils both in situ and in the laboratory (Hanson 1990, Hanson 1991; Hanson and Cook 2004). Tests were performed on 11 gravity core samples, trimmed into 10–12 cm sections. To run the test, a pressure head (h) of 2.1 m was set using a constant head tank, which determined the shear stress applied by an impinging jet of water projected through the mini-JET device nozzle. During testing, the mini-JET device was turned on and off to scour the soil sample located underneath during a predefined time interval. After each time interval, a point gauge was lowered to measure the depth of the generated scour hole. Time intervals of 5, 15, 30, 60, 120, and 300 s were used for testing, with each time interval repeated until three consecutive and approximately equal depth readings were obtained. Fig. 3 illustrates the device throughout testing.

Once the tests were complete, recorded scour depths and time intervals were converted into erosion rates (E). The applied shear stress (τ) was calculated as $\tau_o = C_f \rho U_o^2 (J_p/J)^2$, where $C_f = 0.00416$ is the coefficient of friction, ρ is the water density, $U_o = C_d \sqrt{2gh}$ is the velocity of the water jet at the nozzle, $C_d = 0.74$ is the discharge coefficient, g is the gravitational acceleration, $J_p = C d_o$ is the potential core length, $C = 6.3$ is the diffusion coefficient, $d_o = 3.18$ mm is the nozzle diameter, and J is the measured

scour depth (Hanson and Cook 1997). Erodibility parameters were then determined by fitting the measured E and τ data to the excess shear equation (Partheniades 1965) given by the following equation:

$$E = k_d(\tau - \tau_c)^n \quad (6)$$

where k_d = detachment coefficient; τ_c = critical shear stress; and n = positive numerical exponent typically assumed as unity. Erodibility parameters were obtained by performing a least-squares linear fit to the raw E and τ data with k_d and τ_c being the fitting coefficients. This relatively simple approach has been shown to be more consistent than other available solution methods (Wardinski et al. 2018; Wahl 2021). Goodness of fit was quantified using a normalized objective function, which has been used previously for JET data (Fox et al. 2006; Al-Madhhachi et al. 2013).

For both cohesive and noncohesive sediments, the detachment coefficient, k_d (cm³/ (N · s)), describes the erosion rate of the sediment once erosion has been initiated ($\tau > \tau_c$), and it has units of erosion rate per unit of excess shear stress. Higher k_d indicates more erodible sediment. A companion study was conducted using JET on beach sand and strong correlation ($R^2 = 0.87$) was found between k_d and void ratio, e , via an empirical power-law relationship given by the following equation (Brilli et al. 2024):

$$k_d = 1,396e^{2.5861} \quad (7)$$

Since D_r is related to e by Eq. (8), and D_r can be directly estimated from PFFP measurements [Eq. (2)], it follows that k_d can also be obtained from PFFP measurements for noncohesive sediments

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \quad (8)$$

Minimum ($e_{\min}$) and maximum ($e_{\max}$) void ratios were computed for the coarse-grained sediments from samples obtained via Shippek sampling during the 2021 survey (ASTM D4254-00, ASTM 2006a; ASTM D4253-16, ASTM 2006b). Using these values, Eq. (9) can be used to convert D_r from Eq. (2) into the void ratio and then Eq. (7) gives k_d

$$e_{\max} = 0.72, \quad e_{\min} = 0.43 \rightarrow e = 0.72 - 0.29D_r \quad (9)$$

$e_{\min}$ and $e_{\max}$ values are well in line with expectations (Cubrinovski and Ishihara 2002), despite possible disturbance of samples from grab sampling.

Results

Of the 66 individual sites from which physical samples were collected during the 2021 survey, 25 classified as coarse-grained (fines <50%) and 41 classified as fine-grained, highlighting the variability at the sites. Fig. 4 shows the fines content for all sites sampled during the 2021 survey (Fig. 1).

Only six sites had fines content less than 12%, the traditional United Soil Classification System (USCS) cutoff for clean sand, meaning that a majority of the sites would be considered mixed sediments. The west side of the bay was dominated by fine sediments with a coarse-grained area approximately 10 km offshore of the western coast (Fig. 4). Fine-grained sediments were predominantly found on the eastern side of the bay, closer to shore, with the exception of a sand bank located along the middle line heading offshore. The southern area near the Colville Delta was more mixed with no clear spatial trends on the scale investigated (Fig. 4). While there is no clear consensus on the fines content that

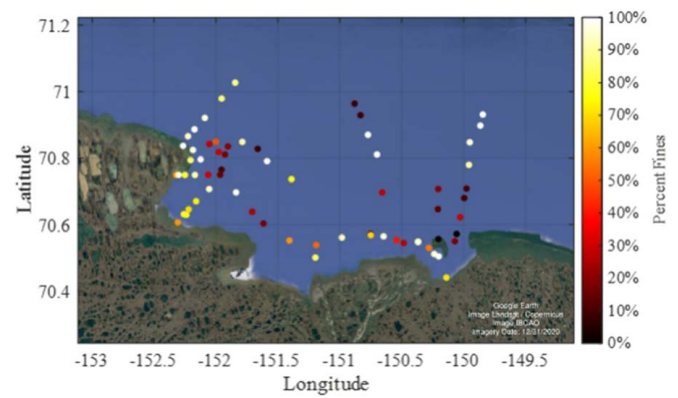


Fig. 4. Spatial distribution of fines contents across Harrison Bay, Alaska. Lighter indicates finer sediment and darker indicates coarser sediment (N70°16'2.16" W153°1'22.75"). (Image © Google, Image Landsat/Copernicus, Image IBCAO.)

determines the boundary between cohesive and noncohesive behavior, 30% fines content has been used repeatedly in both geotechnical and sediment dynamics literature as a threshold to distinguish cohesive from noncohesive behavior, and as such will be adopted here (van Ledden et al. 2004; Yang et al. 2006; van Rijn 2020). Fig. 5 shows 179 PFFP deployments (2–3 deployments at each of the 66 sites) classified using $FF = 450 \text{ m}^{-1}$ into two groups with lighter indicating deployments that were associated with samples having fines content greater than 30%, and darker having fines contents less than 30%. As seen from the figure, a threshold value of $FF = 450 \text{ m}^{-1}$ accurately predicted all 125 deployments with $FF < 450 \text{ m}^{-1}$ as having fines content greater than 30%, and 50 out of 55 deployments with $FF > 450 \text{ m}^{-1}$ as having fines content less than 30%. The five samples that were incorrectly classified are likely due to heavily overconsolidated mud.

Table 1 presents the results of the JET analysis from the gravity core samples taken during the 2022 survey.

Erodibility can be determined by undrained shear strength measurements from the PFFP. A negative power-law relationship between k_d and s_u is apparent for the tested samples (Fig. 6). Furthermore, it was observed that samples having $s_u < 2 \text{ kPa}$, had

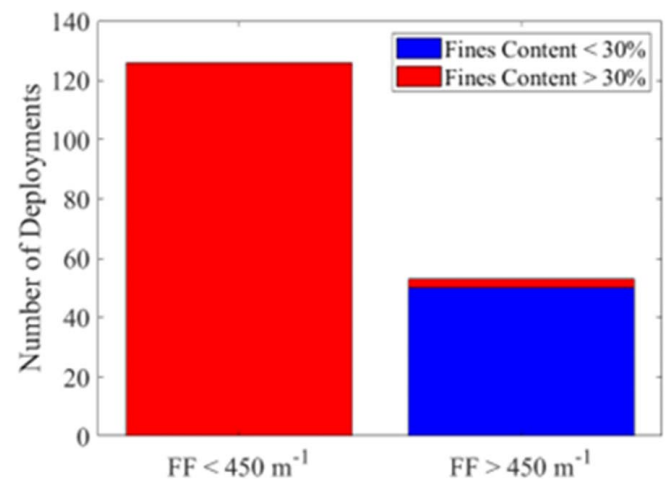
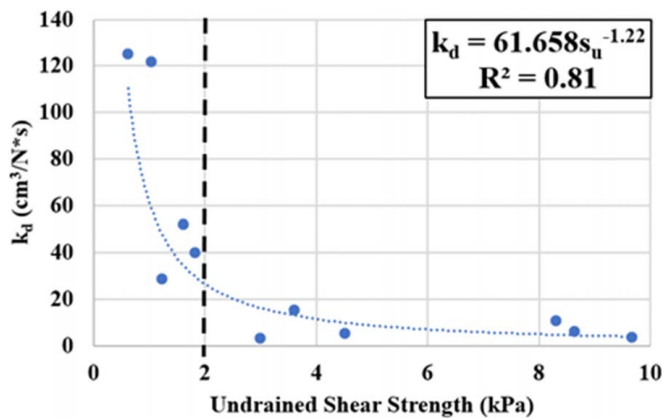


Fig. 5. Distribution of deployments with greater than 30% fines (lighter) and fines < 30% (darker), with the left column consisting of deployments with $FF > 450 \text{ m}^{-1}$ and the right column deployments greater than 450 m^{-1} .

Table 1. Results of JET tests on gravity core samples from the 2022 survey

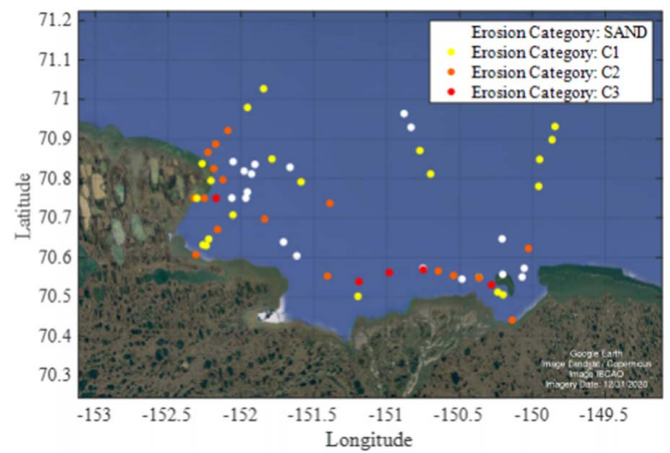
Site	τ_c (Pa)	k_d (cm ³ /N·s)
WP571 #1	4.83	3.57
WP692 #1	5.68	52.08
WP852 #2	4.77	121.65
WP915 #1	16.07	5.13
WP915 #2	12.09	6.25
WP1006 #1	3.93	39.99
WP1012 #1	7.71	125.15
WP1017 #1	10.76	28.54
WP1017 #2	15.56	3.03
WP1021 #1	10.10	15.26
WP1021 #2	6.27	10.84

Note: Samples from the same site labeled “#1” and “#2” indicate a gravity core sample that was longer than 12 cm that can be accommodated by the JET mold and was sectioned into 12 cm increments for testing. Samples labeled “#1” indicate the uppermost sample, and subsequent numbers are consecutive in depth. τ_c values ranged between 3 and 16 Pa, and k_d values ranged from 3 to 120 cm³/N·s.

**Fig. 6.** Relationship between s_u derived from PFFP and k_d from JET for locations where gravity core samples and PFFP deployments were colocated.

k_d values > 20 cm³/N·s, and samples with s_u greater than 2 kPa had $k_d < 20$ cm³/N·s (dashed line, Fig. 6). Hence, this value served as the first threshold for erodibility classification based on PFFP measurements, which is presented in the following sections. Parameters from the PFFP (s_u , FF, a_{max}) were also compared with τ_c from the JETs, but no significant relationships were found between PFFP measurements and τ_c for the data available at this site.

Using the soil classification in Fig. 5, the relationship with D_r in Eq. (9), and the relationship presented in Fig. 6, a classification system was developed for relating PFFP measurements to erodibility. Based on the previously developed criteria for differentiating cohesive versus noncohesive sediments, and relationships between s_u and k_d , the following erodibility categories based on PFFP measurements are suggested (Table 2). Category SAND is defined as any deployment with FF > 450 m⁻¹. This category is the most erodible of the four and encompasses noncohesive sediments with the

**Fig. 7.** Distribution of erosion categories across Harrison Bay including the NC, and the three cohesive categories (C1–C3) (N70°16'2.16" W153°1'22.75"). (Image © Google, Image Landsat/Copernicus, Image IBCAO.)

erodibility parameter k_d falling between 150 and 600 cm³/N·s, based on D_r from the PFFP developed in the study by Brilli et al. (2024) and computed using Eq. (7). Categories C1–C3 are based on s_u for cohesive sediments with FF < 450 m⁻¹. Categories C1 and C2 reflect the delineation made in Fig. 6, with the addition of a buffer of 1 kPa due to a small number of data points and to reflect uncertainty in the measurements. C1 sediments have a slightly smaller range of τ_c values based on the results displayed in Table 1. Finally, Category C3 included deployments with s_u greater than 20 kPa. These sediments fell well outside of the sample data bounded by Fig. 6, and thus, no specific ranges are given for erodibility parameters, with this category simply being described as *least erodible*.

Using the criteria from Table 2, the PFFP deployments from the 2021 survey were converted into their corresponding erosion categories (Fig. 7). The west side of the bay shows a lot of variability with a mixture of C1 and C2 zones along with a large zone of SAND. Sediments seem to be more erodible offshore with most offshore sediments classifying as C1 with the exception of a small area of SAND sediments in the middle of the bay. In the South near the Colville Delta, the least erodible sediments were found, with mostly C2 and C3 sediments, as well as SAND and C1 sediments, sparsely populated within those areas.

A similar approach was taken for the 13 km transect displayed in Fig. 1. First, FF was calculated for each of the 160 PFFP deployments, and they were separated based on cohesive and noncohesive behavior [Fig. 8(a)]. As seen in the figure, a majority of the transect classified as cohesive, with the shoal beginning at approximately 10 km classifying as noncohesive. The series of sand waves starting at 11.5 km also classified as noncohesive, except for select deployments in the trough that classified as cohesive.

The classification system described in Table 2 was used to determine erodibility classifications along the transect, with the variability in sediment properties and erodibility both being

Table 2. Breakdown of erosion categories for cohesive sediments at the Harrison Bay site based on the results of the field and laboratory measurements

Erosion category	Criteria	Determination of τ_c	Determination of k_d
SAND	FF > 450 m ⁻¹	No data for this study	15–600 cm ³ /N·s
C1	$s_u < 2 - 3$ kPa	3–10 Pa	> 20 cm ³ /N·s
C2	$s_u = 3 - 20$ kPa	3–15 Pa	< 20 cm ³ /N·s
C3	$s_u > 20$ kPa	Least erodible	—

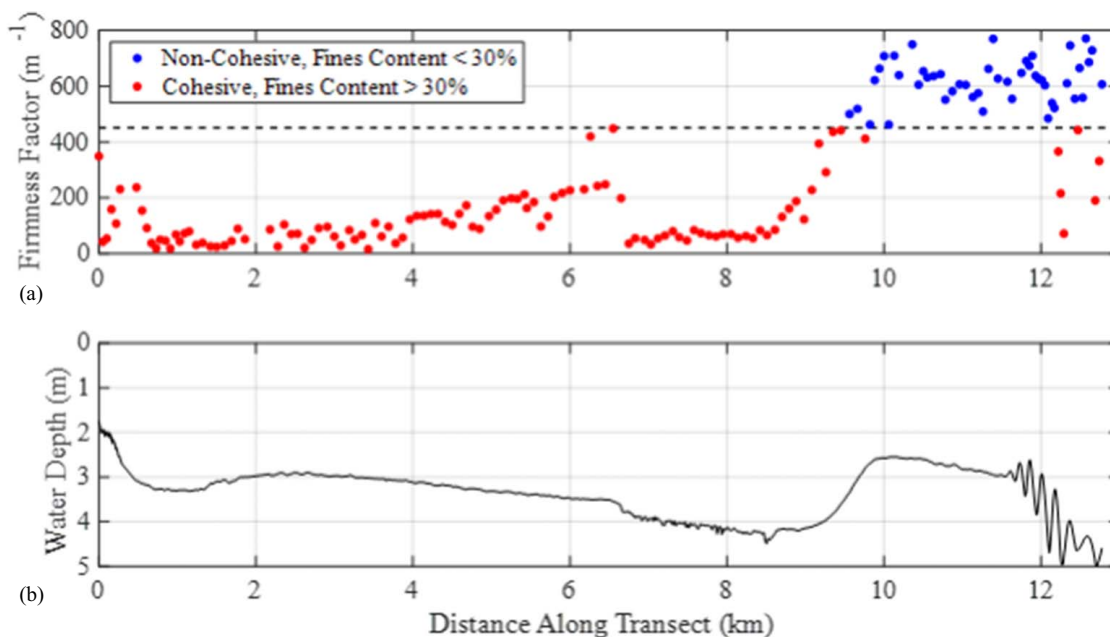


Fig. 8. (a) Application of the firmness factor classification to a smaller 13-km transect off the west coast of Harrison Bay from PFFP deployments; and (b) bathymetry along transect.

highlighted. Fig. 9(a) shows s_u on the left y-axis (only applicable for C classes), and D_r on the right y-axis (only applicable for the noncohesive category class). D_r values ranged from 60% to 90%, representing overall relatively dense sands, which may suggest limited recent mobility. These values of D_r are in line with the work by Albatal et al. (2020), who developed the correlation and applied it to nearshore deployments in similar water depths. There was significant variability in s_u across the transect with values ranging from <1 to 50 kPa, representing very soft to very stiff fine-grained seabed surface sediments. This is a wider range of s_u than presented by Jaber and Stark (2023), who derived s_u from PFFP measurements for $s_u < 10$ kPa. The work in that study was focused on soft estuarine and coastal sediments, but Harrison Bay additionally featured stiffer, overconsolidated muddy sediments. This variability is also reflected in the erosion categories. The x-axis on the Fig. 9(b) translates each category onto a line for better visualization with the bathymetry. The initial depression from 0.5 to 2 km contained weak, highly erodible sediments, with strength increasing and erodibility decreasing across a flatter, sloping bed until a second depression around 7 km, where the sediment became soft and erodible again in a zone likely affected by ice scours. This was followed by a sharp increase in s_u (decrease in erodibility) until the sediment transitioned to noncohesive at which point the shoal was dominated by highly erodible SAND sediments, with the exception of less erodible C2 and C3 sediments in the troughs of the sand waves starting at 11.5 km.

Discussion

The results of this study show that surficial seabed sediments in Harrison Bay, Alaska, are highly variable in both geomechanical properties and erosion behavior. The observed surficial sediment variability was also noted by Barnes (1980) and is likely due to a wide variety of sediment inputs and ice gouging causing reworking of the uppermost sediment layers (Barnes and Reimnitz 1974; Reimnitz et al. 1977; Barnes et al. 1985). The variability in sediment properties and erodibility in Arctic environments has important

implications for applied engineering applications in these areas such as for the protection of buried pipelines and for improving numerical models of shelf morphodynamics in response to climate change (Nematzadeh and Shiri 2020; Hashemi et al. 2022; Malito et al. 2022). However, remote fieldwork logistics, coupled with limited access to Arctic nearshore areas due to sea ice most of the year, make sediment characterization from physical samples, erodibility assessment from in situ coring, and geotechnical strength estimation a difficult proposition. This highlights the utility of the proposed framework, where the PFFP was used to differentiate cohesive and noncohesive sediments, and furthermore, to distinguish different categories of erodibility (Fig. 5 and Table 2).

Sediment and Erodibility Classification Scheme Based on PFFP Measurements

The methodology presented in the results for using PFFP measurements to classify sediment behavior type and erodibility behavior is summarized in Fig. 10. The first step is to calculate FF directly from the PFFP data [Eq. (1)]. Distinguishing cohesive versus noncohesive sediments (Fig. 5) is important as these two groups behave differently in terms of sediment properties, strength, and erodibility (NASEM 2019). While there is no consensus agreement on 30% fines being a unique cutoff between cohesive and noncohesive behavior, it is widely recognized as an acceptable value here (van Ledden et al. 2004; van Rijn 2020). Values as low as 10% and as high as 40% have also been suggested as thresholds, but 30% will be adopted here to stay consistent (Yang et al. 2006; Jacobs et al. 2011). The value of $FF = 450 \text{ m}^{-1}$ represented a reliable threshold for cohesive and noncohesive sediments based on this fines content of 30% with 96% of tests classifying correctly (Fig. 5).

The five observed outliers can be explained by the presence of heavily consolidated, stiff cohesive sediments. This type of regional sediment mapping using FF and other parameters from PFFP deployments has been demonstrated before (Mulukutla et al. 2011; Albatal and Stark 2017), but this is the first application of this type of analysis to an Arctic environment, and further serves

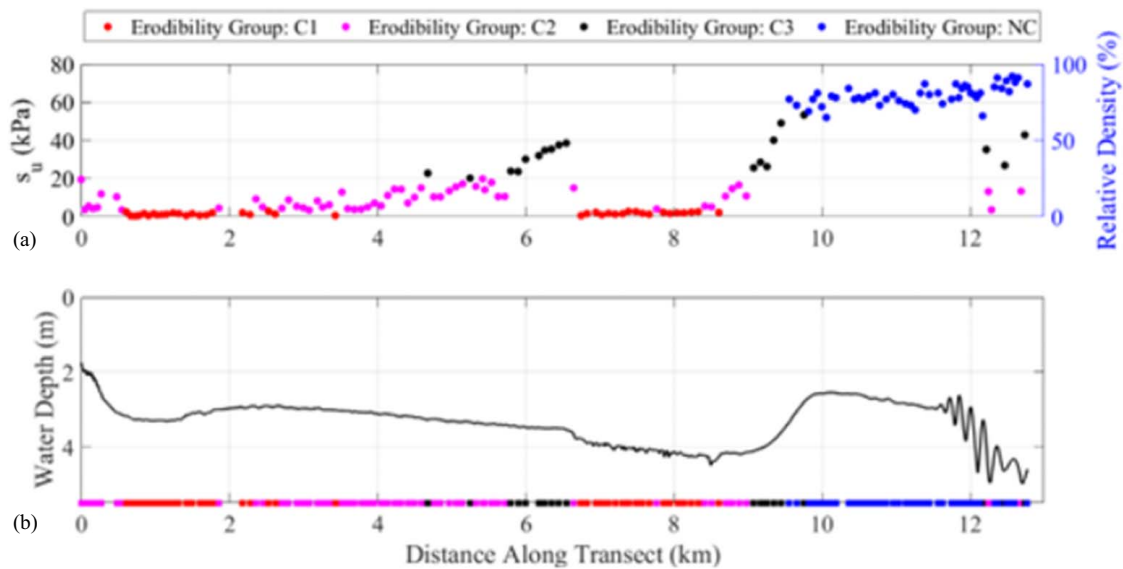


Fig. 9. (a) Application of erosion categories to the same transect from Fig. 8 using the PFFP deployments with s_u on the left y-axis (only applicable for C classes) and D_r on the right y-axis (only applicable for the NC class) and (b) bathymetry along with colored sections to visualize erodibility zones more easily.

the purpose of laying the foundation for deriving erodibility categories as proposed in Table 2 with measurements being faster and easier to perform than grab sampling or coring.

Following the left side of the flow chart, the next step is to calculate D_r from Albatal et al. (2020) [Eq. (2)] and using this value to compute k_d via Eqs. (7)–(9). There were no direct comparisons made between erodibility parameters and geotechnical properties for noncohesive sediments at this site as there were no undisturbed in situ samples of sandy sediments taken for JET. Gravity cores generally do not yield good cores in cohesionless soils. Data available from JET on high quality in situ cohesionless samples from a companion study (Brilli et al. 2024) and laboratory tests on sand from grab samples allowed for a range of k_d values to be computed for the noncohesive stations in Harrison Bay. For the

SAND classification, it is suggested that τ_c can be obtained via empirical relation. While no in situ data are available from this site, van Rijn (2020) suggested that empirical relations can give a reasonable estimate of initiation of motion (Shields 1936; Brownlie 1981; Soulsby and Whitehouse 1997; van Rijn 2007).

For sediments classifying as cohesive, s_u is calculated from Eqs. (3) to (5). The three categories, C1–C3, are then differentiated using the relationship in Fig. 6, showing a correlation between k_d and s_u . A first threshold value was chosen at $s_u = 2$ –3 kPa, as samples with s_u less than this value had $k_d < 20 \text{ cm}^3/\text{N}\cdot\text{s}$. The value of $s_u = 20$ kPa was selected as an upper threshold, as it was outside of the range of s_u presented in Fig. 6 (0–10 kPa), with 20 kPa being selected to add conservatism to the model test over a limited

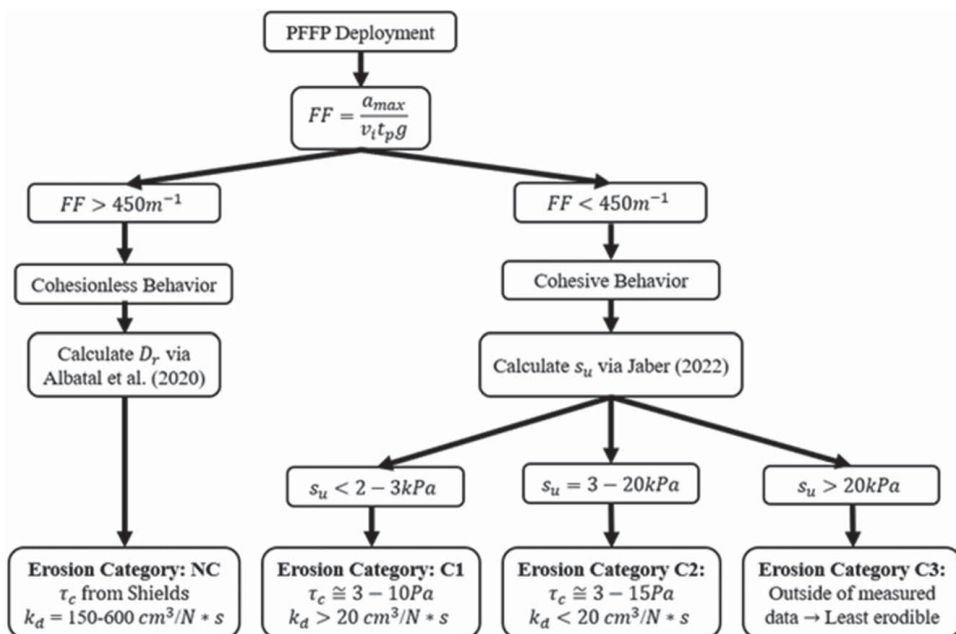


Fig. 10. Flowchart describing data analysis and breakdown of erosion categories based on geotechnical sediment properties.

range of s_u . There were no relationships found between τ_c and PFFP parameters for the cohesive sediments. Therefore, the range presented in Table 2 and Fig. 10 represent the range of values directly from the JET measurements in Table 1. It should be noted that there is considerable uncertainty involved with predicting initiation of motion, and the values presented must be considered an order of magnitude estimate of the initiating stress. Still, values of τ_c from the JET are in line with typical ranges, with previous studies showing τ_c up to 20 Pa (Kamphuis and Hall 1983). It is acknowledged that the magnitude of measured τ_c values are large enough to where sediment suspension and transport would be occasional and infrequent on a wave-by-wave basis, and the large stresses required to initiate erosion would lead to difficulties in predicting shelf evolution over short timescales. Furthermore, weak, highly erodible surface sediments, such as in areas of recent deposition from bluff erosion or ice scouring (Fig. 9), could have values of τ_c orders of magnitude lower than the reported range for C1 material, as the ranges were bounded by the available results from the JET. Transport of these loose, unconsolidated surface sediments would be achievable on a wave-by-wave or current driven basis. It is advised that the erosion rate values in the characterization scheme are given preference when utilizing the scheme for timescales on the order of seconds to days or when investigating energetic events with higher expected shear stresses reaching beyond recently deposited surface sediments. For long-term processes (100–1,000 years), the order of magnitude estimates of τ_c are considered reasonable, as much longer timescales would be required to observe appreciable changes in bathymetry given the large values of τ_c . Hence, the characterization scheme presented in Fig. 10 could be useful particularly when developing long-term morphological models of shelf evolution or assessing erosion in response to energetic events. However, it may underestimate erosion of uppermost and recently deposited surface sediments.

Application of Classification Methodology in the Context of Local Geomorphodynamics

Analyzing the erosion categories in the context of the local site conditions offers further insights. Fig. 7 suggests that Harrison Bay is overall highly variable in sediment properties including erodibility. The west side of the bay features a majority of fine sediment (Fig. 4) classifying as a mix of C1 and C2. This suggests that while the fines contents may be similar, the sediments feature different strengths and a different mobilization behavior. Zooming in to the 13 km transect detailed in Figs. 8 and 9 further illustrates this point. Specifically, the zones of C1 material in the depressions located at 0–2 and 7–9 km can be understood in the context of local sediment transport and ice processes. The start of the transect is located less than 1 km offshore, and the shoreline on this side of the bay is marked by bluff erosion. Héquette et al. (2001) suggested that coastal bluffs induce wave energy reflection, especially during storm events, which can drive offshore directed bottom currents. Freshly eroded unconsolidated bluff sediments and organics would be transported offshore by this process and deposited in the depression at 0–2 km, explaining why this zone primarily comprised soft, highly erodible sediments. Further, the zone of sharp transition (over an approximately 100 m distance) from the least erodible C3 sediments into a zone of soft C1 sediments (see the x-axis approximately 6.5 km) marked by small bathymetric undulations (on the order of 5–30 cm) can be explained by ice-gouging processes. Reimnitz et al. (1977) found that ice gouging of the seabed could completely rework bottom sediments in the upper 20 cm, which is directly in line with the

magnitude of scour seen in Fig. 9. The sharp transition from C3 to C1 sediments over a short spatial extent can be explained by the knickpoint commonly found on the inner edge of ice-gouging zones, typically comprising coarser sediments (Reimnitz and Kempema 1983). The addition of coarser particles to sediments with cohesive behavior would account for the sharp increase in s_u and decrease in erodibility (Torfs et al. 2000). Even over a small area of the bay (13 km transect within 70 km), there are large variations in sediment properties and erodibility. The proposed framework in Fig. 10 allows to assess the erodibility behavior of Arctic seabed sediments in the context of local sediment transport and sea ice processes, highlighting the utility of this methodology as a robust tool for understanding local sediment dynamics over a range of spatial scales.

Conclusions

Understanding sediment dynamics in Arctic environments is key to understanding how these systems will respond to climate change. A key question in the area of sediment dynamics is the quantitative relationship between sediment strength properties (that can be easily measured in situ) and erodibility. PFFP measurements and the derived seabed firmness factor were able to create a classification scheme for cohesive versus noncohesive sediments, and beyond that for four erodibility categories. The main findings are summarized as follows:

1. A regional sediment classification scheme was developed using $FF = 450 \text{ m}^{-1}$ as a threshold for differentiating cohesive ($FF < 450 \text{ m}^{-1}$) and noncohesive ($FF > 450 \text{ m}^{-1}$) sediments with 96% accuracy.
2. Undrained shear strength, s_u , shows a clear relationship with detachment coefficient, k_d , obtained from JET, highlighting a relationship between geotechnical properties of fine-grained sediments and erodibility parameters. This is particularly important, as s_u is easily obtainable from PFFP deployments.
3. A dual sediment strength characterization and erodibility classification framework was developed using PFFP measurements and divided into four erosion categories. The noncohesive SAND category obtains critical shear stress, τ_c , from empirical relations and k_d from PFFP estimates of D_r . Three cohesive sediment categories (C1–C3) were differentiated using the derived s_u relationship with k_d . The value of τ_c varied from 5 to 15 Pa and was obtained from direct measurements from the JET. The estimates of $s_u < 2$ and 3 kPa yielded the most erodible category (C1) with $k_d > 20 \text{ cm}^3/\text{N}\cdot\text{s}$. Deployments with s_u between 3 and 20 kPa represented Category C2, with $k_d < 20 \text{ cm}^3/\text{N}\cdot\text{s}$, and the final category, C3, was the least erosive sediment with $s_u > 20 \text{ kPa}$.
4. This framework was applied to PFFP deployments across Harrison Bay, Alaska, and for a 13 km transect near a permafrost bluff shoreline. The results highlighted the variability of seabed sediment strength and erodibility. Analysis of the transect showed how this framework could associate erodibility with local sediment dynamics and ice-gouging processes.

This framework can help characterize sediment erodibility in environments that are difficult to access, providing high-resolution data that show strongly variable seabed conditions. The measurements of sediment strength and erodibility will improve future site characterization and modeling efforts, particularly in response to long-term processes and energetic events that affect more than just uppermost surface sediments, to predict Arctic response to climate change.

Data Availability Statement

Some or all data, models, or codes generated or used during the study are available in a repository online in accordance with funder data retention policies. The data sets associated with the results presented here are published with the Arctic Data Center and are available at: “Seabed grain-size data from Harrison Bay (Beaufort Sea continental shelf), Alaska 2021,” Eidam (2023) and “Alaskan Beaufort Shelf Sediment Study—Harrison Bay: Geotechnical Properties from a Portable Free-Fall Penetrometer and Erodibility Assessment, 2021–2022,” (Brilli et al. 2023).

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