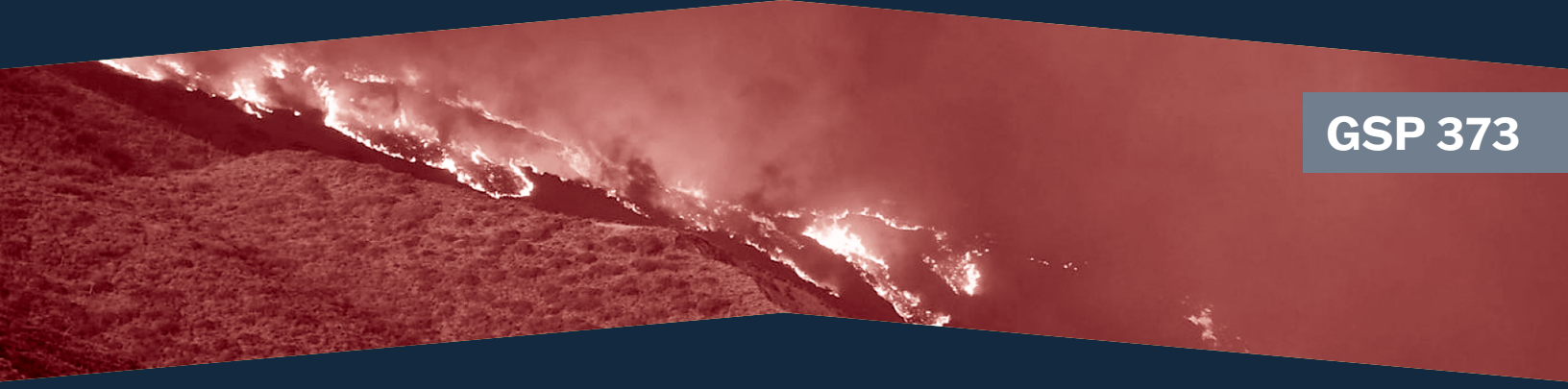


GSP 373

Geo-Extreme 2025



Permafrost, Wildfires, and Other Emerging Challenges in Geotechnical Engineering



Selected Papers from Geo-Extreme 2025
Long Beach, California • November 2–5, 2025

EDITED BY

Christopher L. Meehan, Ph.D., P.E., BC.GE;
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and Ming Xiao, Ph.D., P.E., BC.GE

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Preface

The Embankments, Dams, and Slopes (EDS) Technical Committee of the ASCE Geo-Institute organized a timely and interesting specialty conference in 2021 in Savannah, Georgia, entitled *Geo-Extreme 2021: Geotechnical Engineering for Extreme Events*. This 2021 conference was intended as an inaugural specialty conference, and the beginning of a series of planned conferences organized by the EDS committee seeking to address the many societal challenges that are posed by extreme events such as: earthquakes, hurricanes, landslides, debris flows, wildfires, tornadoes, extreme rainfall events, blizzards, and other extreme loading events caused by changing weather patterns. This 2021 conference built on three previous slope stability related conferences that were organized by the EDS committee, two in 1966 and 1992 at the University of California at Berkeley and one in 2013 in San Diego. Strong impetus for that meeting was provided by a number of very significant extreme events in the United States, starting with Hurricanes Katrina in 2005 and Sandy in 2012 followed by Hurricanes Harvey, Irma, and Maria in 2017, and then Hurricanes Laura, Delta, and Zeta in 2020, which all caused widespread damage to communities at large, and particular damage to natural slopes and engineered structures that are the purview of the EDS Committee.

Since the 2021 conference, the onslaught of extreme loading events in the United States has continued unabated, with significant loss of life and severe financial consequences to communities that are unprecedented. The impact of major hurricanes including Ian, Ida, Idalia, Helene, and Milton has been strongly felt in coastal communities but also ranging far inland. Extreme rainfall and flood events have caused damages averaging in excess of a billion dollars annually, particularly in California. Severe storms, winds, and flooding also battered Kentucky heavily in 2025. Wildfires brought significant destruction and caused numerous deaths in Hawaii's Lahaina fire of 2023, the Smokehouse Creek fire in Texas and Oklahoma in 2024, and in California with the Park Fire in 2024 and wildfires in Southern California in 2025. The 2023 fire season was also particularly significant in Canada, which saw 45,700,000 acres of land burn across ten provinces and three territories.

Following these extreme events, the EDS Committee has proposed and organized the current specialty conference, *Geo-Extreme 2025: Geotechnical Engineering for Extreme Events*. The goal of this conference is to continue to draw attention to the pressing problems posed by extreme events, and to identify the critical role that geotechnical engineers and the civil engineering profession as a whole can play in mitigating the effects of these events, both before they occur, as well as after – that is, "building back safer" in a way that benefits both the built and natural environments.

Historical records show that the number of billion-dollar extreme events are on the rise. Mitigating the consequences of future extreme events requires geo-professionals taking timely actions, including evaluation of existing earthen structures, design and construction of protective structures in areas where an increased probability of damage is expected, refinement of existing geotechnical designs, and development of new adaptive measures and risk assessment tools. To achieve these objectives, the Geo-Extreme 2025 conference will comprise a multi-disciplinary forum between geotechnical engineers and other professionals from related disciplines, such as scientists, various

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types of engineers, emergency managers, resilience and sustainability investigators, insurance experts, and policy makers, to provide solutions that properly cope with and address the wide variety of extreme events that can occur.

There are five volumes containing the full collection of papers presented at Geo-Extreme 2025: Geotechnical Engineering for Extreme Events, which was held on November 2-5, 2025, in Long Beach, California. These five volumes are subtitled: (1) Remote Sensing, Instrumentation, Big Data, and Decision Making, (2) Geotechnical Earthquake Engineering, (3) Civil Infrastructure, Geomaterials, and Case Histories, (4) Different Climates and the Coastal Zone, and (5) Permafrost, Wildfires, and Other Emerging Challenges in Geotechnical Engineering, respectively. These five volumes include over 130 contributions that span 25 subtopic areas of the conference, as noted in the subsequent tables of contents for each volume. Each of the five volumes are Geotechnical Special Publications (GSPs), containing papers that were reviewed in accordance with ASCE GSP standards. Each paper was subjected to technical review by two or more independent peer reviewers, and publication required concurrence by at least two peer reviewers.

The Editors gratefully acknowledge the immeasurable contributions of the countless individuals who made Geo-Extreme 2025 and these published proceedings possible, especially the reviewers, session chairs, organizing committee members, and ASCE staff listed in the acknowledgements.

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The conference and its published proceedings would not have been possible without the diligent, coordinated effort of numerous people, especially the reviewers who provided detailed feedback on papers and the session chairs who made decisions and provided editorial assistance on selected topics. The editorial team is also profoundly grateful to Dr. Daniel Pradel and Dr. Navid Jafari (Conference Co-Chairs), the Technical Program Committee (listed below), Mr. Brad Keelor, Ms. Aurora Phlegar, and the ASCE publications team for their crucial roles in the production of these proceedings.

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Coincident Measurements of Soil Strength and Permafrost Active Layer on the North Slope, Alaska

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ABSTRACT

The North Slope of Alaska is an area susceptible to permafrost thaw, posing significant threats to infrastructure stability. Accurate characterization of soil strength and permafrost active layer depths is crucial for predicting and mitigating these risks. As part of a multi-institution, multi-disciplinary effort, researchers from the US Army Engineer Research and Development Center, the University of Colorado Boulder, and Texas A&M University employed dynamic cone penetrometers (DCP) to investigate the mechanical properties of soils on the North Slope. The tests were conducted in an attempt to identify areas with unstable permafrost and infer potential surface characteristics that may aid in predicting the location of permafrost in the future. Over 200 DCP measurements were collected, with results showing trends along transects running up and down-slope from a small river. The DCP technique offers a cost-effective and rapid method for characterizing soil strength and permafrost stability, making it an attractive tool for future studies and practical applications. This research contributes to our understanding of the complex interactions between geology, terrain dynamics, and infrastructure on the North Slope, ultimately informing strategies to potentially mitigate the impacts of permafrost thawing.

INTRODUCTION

Temperature plays an integral role in predicting thermo-hydromechanical soil properties, particularly key soil strength and soil stability properties like moisture, infiltration, hydraulic conductivity, and mechanical strength (Moore, 1941; Burt and Williams, 1976; Cookson et al., 2007; Nguyen et al., 2019; Redmile-Gordon et al., 2020). Across the Arctic and sub-arctic, permafrost degradation is modifying northern ecosystems through substantial changes in soil water content, soil nutrient availability, and vegetation succession (Jorgenson et al., 2006; Schuur and Mack, 2018). While natural variations in air temperature throughout the year are

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expected in any given ecosystem, unprecedented warming is adding rapid spatial and temporal change to the already highly heterogeneous system (Barker et al., 2014; Douglas et al., 2020).

The Arctic is actively transforming in some areas from intact, stable soil systems to thermokarst wetlands on the timescale of years (Lewkowicz and Way, 2019) whereas other areas are predicted to 'dry out' over time (Andresen et al., 2020). Current soil models have difficulty capturing this change unless they incorporate information on hydraulic and thermal properties derived from landscape information (O'Connor et al., 2020). Thermokarst formation (ground subsidence due to subsurface ice features melting) alters soil moisture in certain areas where the accumulated water is able to drain and the soil then becomes dryer, or, in other areas that have restricted drainage, the shallow subsurface may become heavily saturated (Schuur et al., 2007). Soils that become wetter over time may accelerate permafrost degradation in nearby areas, decrease stability, and alter the breakdown mechanisms of carbon species found in soil (Gutierrez et al., 2008; Dagg and Lafleur, 2011; Hjort et al., 2018). As permafrost degrades ground reliability is directly impacted (Hjort et al., 2018) due to increased water volume, increased downward percolation, and reduced mechanical strength of sediments (Gutierrez et al., 2008). This work seeks to use soil strength measurements to aid in estimating how permafrost thaw is altering landscape-scale terrain dynamics and evaluate how DCP can be used to evaluate that change.

STUDY SITE

The study site (Figure 1) is in the Imnaviat Creek watershed, located approximately 10 km east of the Toolik Lake Field Station in a shallow basin at the foot of the central Brooks Range (Barker et al., 2023; Fuson, 2024; Walker et al., 1989). Recent work shows the site is undergoing significant permafrost thaw (Fuson, 2024). Much of the study site features "retransported deposits" which are predominantly fine-grained, organic-rich materials that have been transported downslope.

The ridge crest features exposed and rocky glacial till. Further description of the field site, as well as visual images of soil profiles can be found in Barker et al. (2023).



Figure 1. Location of Imnaviat Creek on the North Slope of Alaska (Background: Google Earth)

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METHODS

Dynamic Cone Penetrometer

The primary means by which the active layer thickness is measured in the field is the frost probe, which is a thin metal rod typically 1.0-1.5m long pushed into the ground until the operator reaches a point of refusal and can feel that they have reached frozen soil (Boike et al., 2021). The depth is recorded using graduated marks on the side of the probe. While the portable cone penetrometer provides repeatable and continuous geotechnical profiles in difficult soft-soil environments, preliminary trials in Fairbanks, AK, showed that the soils are typically too stiff for hand-pushed operation. In addition, due to the remote nature of the site and susceptibility of the site to anthropogenic alterations, using something like a track-mounted cone penetrometer was ruled out. Given that it possesses a similar shape and dimensions as a frost probe and features a high degree of portability (i.e. all equipment fits in a standard backpack) of the PANDA Dynamic Cone Penetrometer (DCP), it represents a potentially ideal means to capture both geotechnical and active layer properties simultaneously (Hubler and Hanley, 2021; Langton, 1999). The "point of refusal" at which penetration was minimal to none, and Q_d drastically increased is taken as the transition point to fully frozen and used to determine the thickness of the active layer. An example sounding from the site is shown in Figure 2.

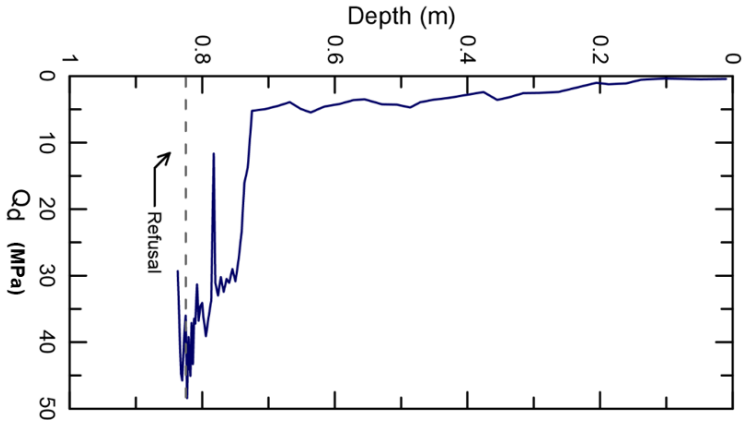


Figure 2. Example DCP profile showing depth of refusal used to determine Active Layer Thickness

Elevation Data

Elevation data was processed from the ArcticDEM dataset provided by the University of Minnesota Polar Geospatial Center to Google Earth Engine (Porter et al., 2018). Elevation data is provided at a pixel resolution of 2m. Using Python and Google Earth Engine, the latitude and longitude pair of coordinates for each testing location was matched against a corresponding list of pairs of coordinates in the ArcticDEM. The closest point to each testing location was used to determine the elevation of the testing site. While the authors acknowledge that the elevation data is likely inaccurate due to the significant topographical variations occurring due to permafrost thaw-induced subsidence, the ArcticDEM provides the best available continuous spatial coverage at the time of this publication.

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Transect Creation

To investigate possible trends of active layer thickness with change in elevation from the creek upslope to the ridge, the PANDA data was filtered into six horizontal transects using Python (Figure 3). A bucket tolerance of 0.001 degrees of latitude was used to separate each line, and points were then automatically separated. As the layout of the site is not perfectly aligned with equal spacing of tests between latitudes and longitudes, the created transects do not align perfectly in straight lines from the creek to the ridge.

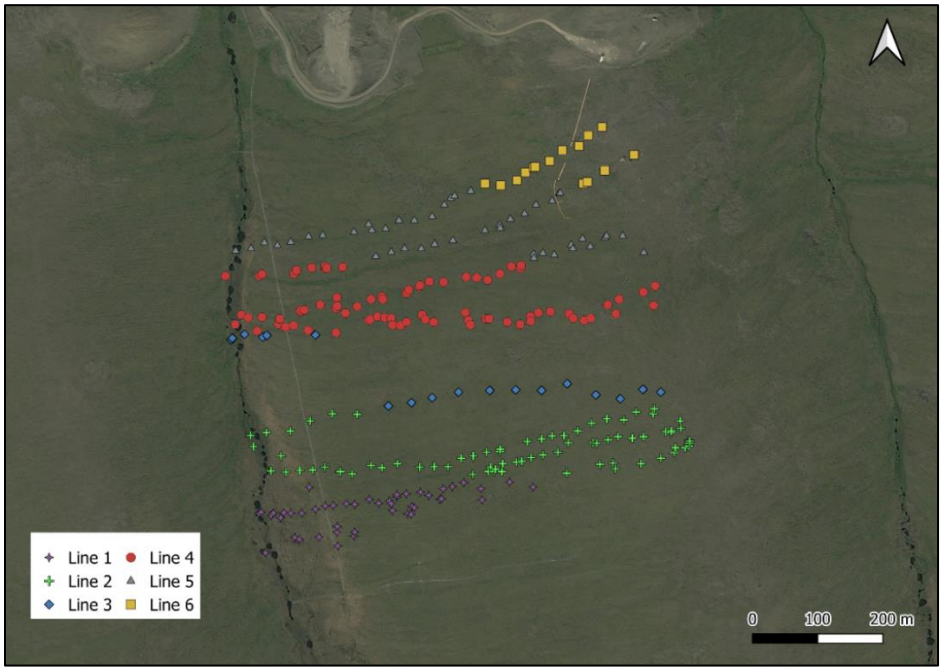


Figure 3. Transects as binned by Latitude (Background: Google Earth)

RESULTS

Profiles of the surface elevation and active layer thickness for lines 1-6 at the site are shown in Figure 4. Figure 4(a) represents line 6, the furthest north site and the site closest to the Dalton Highway. Figures 4(b-f) represent the transect lines moving further south. No discernable trends are present in terms of the active layer thickness with surface elevation. Figure 4(f) shows the presence of a test located directly adjacent to the creek edge which exhibited the greatest depth of penetration of all tests at nearly 1.4 m. Figure 4(e) features the most complete transect line (line 2), which is selected for further investigation in Figure 5. The variance in measured active layer thickness illustrates the ability of the DCP to satisfy the requirements of capturing the small-scale variability in thaw depth mentioned in Boike et al. (2021).

The summary statistics of the active layer thickness and Q_d at the interface layer for the entire Imnaviat Creek site are shown in Table 1. Active layer thickness ranges from 0.35 m (1^{st} percentile) to 0.76 m (99^{th} percentile), with a minimum thickness recorded of 0.02 m (i.e. rock near surface) and a maximum thickness of 1.33 m recorded adjacent to the creek.

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Table 1: Summary Statistics of Active Layer Thickness and Q_d at Interface Layer

	Active Layer Thickness (m)	Q_d (MPa) At Interface
1st percentile:	0.35	17.14
25th percentile:	0.49	32.02
50th percentile:	0.52	36.57
75th percentile:	0.57	45.90
99th percentile:	0.76	76.83
Minimum:	0.02	4.98
Maximum:	1.33	124.28
Mean:	0.53	39.04
Median:	0.52	36.57
Variance:	0.01	131.87
Standard Deviation:	0.08	11.48
Interquartile Range:	0.09	13.88
Standard Error:	0.00	0.20
Coef. of Variation:	0.14	0.29
Skewness:	0.92	1.32

Walker et al. (1989) provided a comprehensive overview of the Imnaviat Creek study site, including idealized toposequences spanning from the creek up-slope to the ridge (Table 2). The slope is delineated into several distinct toposequence units, with the typical distance up-slope from the creek that the unit is found, the thickness of the insulative moss mat on the surface, the active layer thickness, a description of ground ice content, and the vegetation types.

Table 2: Idealized Toposequence at Imnaviat Creek Site (Walker et al. 1989)

Toposequence Unit	Distance From Creek Up-Slope (m)	Insulative Moss Mat	Active Layer Thickness (cm)	Ground Ice Content	Vegetation
Crest	700-900	<2 cm	80	Low	Dry prostrate-shrub, fruticose-lichen tundra
Shoulder	600-700	<5 cm	70	Low	Dry dwarf-shrub, fruticose-lichen tundra
Upper Backslope	400-600	5-10 cm	43	Moderate	Moist tussock-sedge, dwarf-shrub tundra
Lower Backslope	200-400	10-20 cm	30	High	Moist dwarf-shrub, tussock-sedge (or nontussock-sedge) tundra
FootSlope	0-200	>20 cm	30	High	Moist (or wet) dwarf-shrub, moss tundra

Figure 5 shows the measured active layer thickness on line 2 from the summer of 2024 plotted against the active layer thickness in the idealized toposequence at the Imnaviat Creek Site. The active layer thickness in the idealized toposequence exhibits the greatest difference from the measured thickness in the footslope region, characterized by the space from 0-200m from the creek to up-slope. Sharp decreases in the active layer thickness in the footslope region

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could be due to striking rocks or other coarse material. The idealized trend of active layer thickness is closest in the Upper Backslope toposequence and is greater than the measured thickness further up-slope in the Shoulder region. The near-linear trend of decrease in the active layer thickness across the Footslope and Lower Backslope could be due to a zone of influence around the Creek leading to increased thaw. The rate of change in active layer thickness with distance is approximately 1 mm/m from the toe of the Footslope to the beginning of the Upper Backslope.

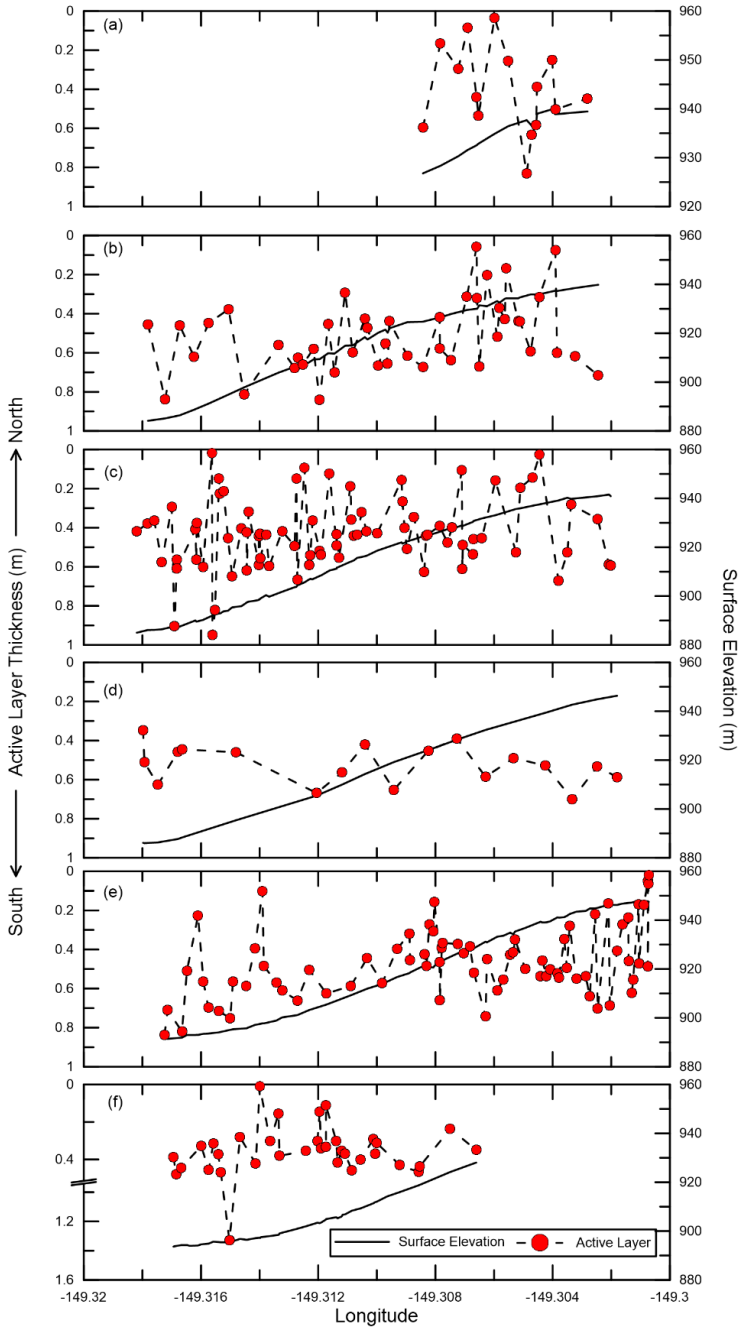


Figure 4. Active layer thickness and surface elevation as a function of longitude for (a) Line 6, (b) Line 5, (c) Line 4, (d) Line 3, (e) Line 2, and (f) Line 1 as denoted in Figure 4.

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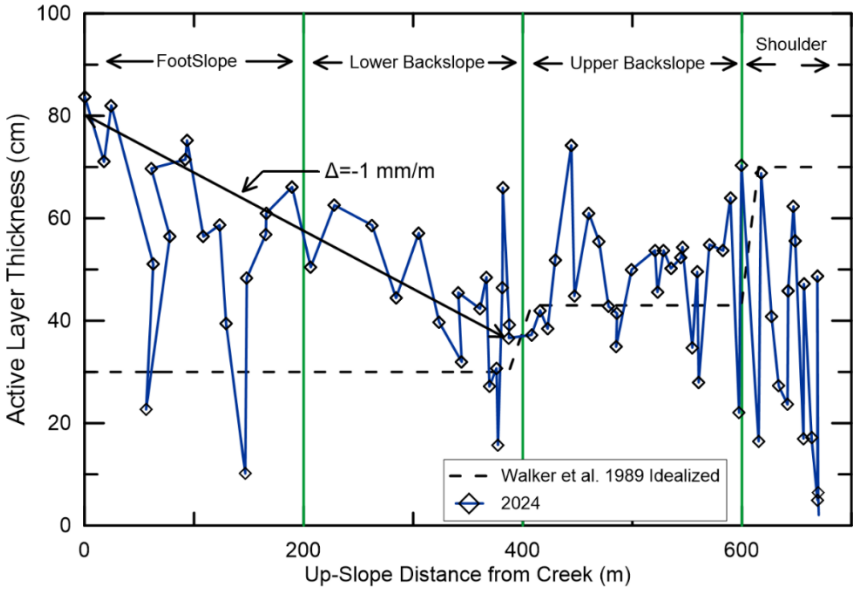


Figure 5. Active layer thickness measured with DCP and thickness by idealized toposequence from Walker et al. (1989).

A generally non-linear relationship between the number of blows struck on each sounding and the maximum depth below the surface is shown in Fig. 6. Due to the remote nature of the study site, and lack of telecommunications services which could be used for technical troubleshooting in the field, the trend in Fig. 6. indicates that on the North Slope site a rough estimate of depth could be given if the operator of the DCP keeps track of the total number of blows.

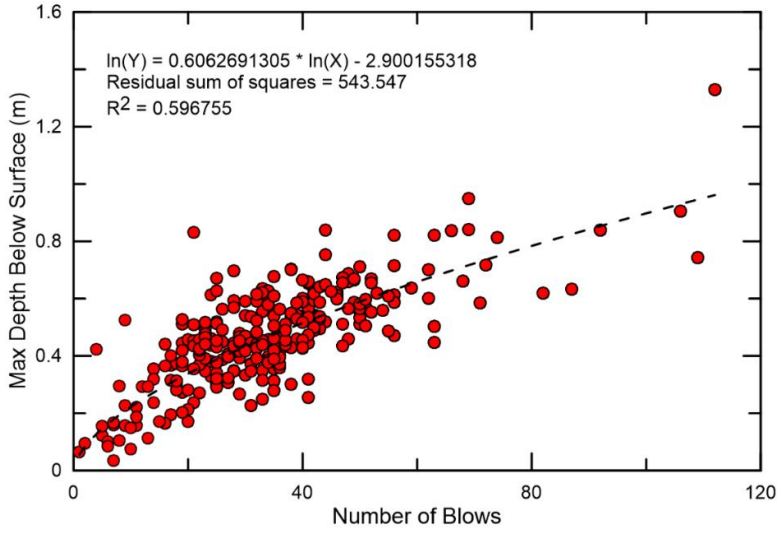


Figure 6. Maximum Depth Below Surface as a Function of Number of DCP Blows

Interestingly, and with implications for future work involving the DCP in the Arctic, there are visually noticeable but not statistically significant differences in the measurements depending

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on who is operating the equipment. To identify potential operator-dependency in the data, two separate teams obtained DCP soundings with identical equipment in overlapping locations. As seen in Figure 7(a), the slope of Q_d with depth is lower for the "Cadigan Team" as compared to the "Harris Team." In Figure 7(b), it is also clear that the active layer thickness measured by the "Harris Team" was approximately 10 cm greater than the "Cadigan Team." These differences should be accounted for in future work, and further study is needed to quantify the repeatability and statistical uncertainty of measurements using the DCP in the Arctic.

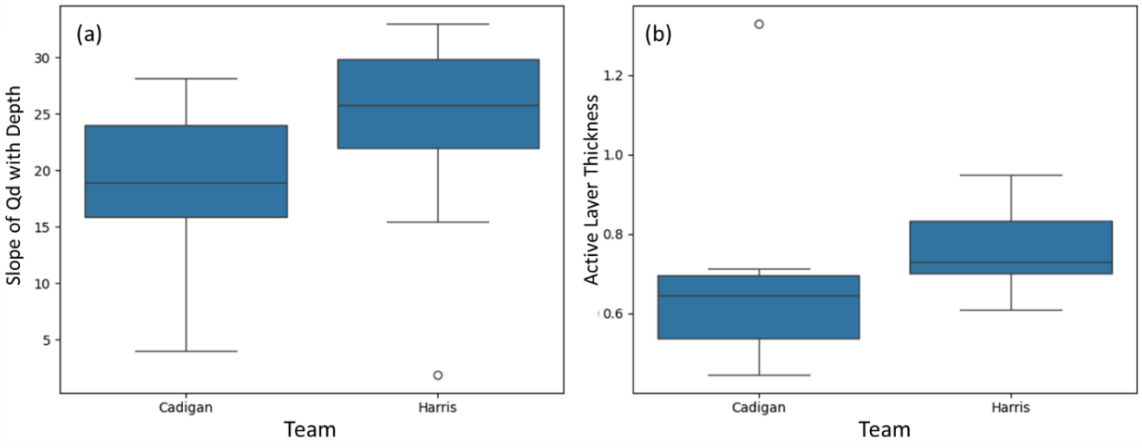


Figure 7. Operator-dependent differences in (a) slope of Q_d with depth, and (b) active layer thickness.

CONCLUSIONS

The PANDA DCP was used to determine the active layer thickness at the Imnaviat Creek study site in northern Alaska. DCP measurements illustrated where the location of frozen soil began, allowing for rapid determination across a large spatial scale of the active layer thickness by researchers on foot, minimizing the anthropogenic disturbances expected from typical geotechnical measurements on the site. The field measurements were compared against idealized profiles of active layer thickness at the site from Walker et al. (1989). Interestingly, the greatest deviation from the idealized profile occurred nearest the creek, where it is hypothesized that the water within the creek exerts a zone of influence on thaw depth. The decrease in active layer thickness with distance from the creek up-slope was nearly linear, with a rate of change of approximately 1 mm/m. Given the nature of applied research in difficult environments such as Imnaviat Creek, the finding that depth was largely correlated non-linearly with the number of blows exerted could allow researchers to continue to identify the active layer thickness using the PANDA even in the case of equipment malfunction which cannot be repaired in the field. There were also visually identifiable, but not statistically significant, differences in both the slope of Q_d with depth and the measured active layer thicknesses between the two research teams which took part in the study. Further work is needed to quantify the repeatability and uncertainty involved with using the PANDA in Arctic environments.

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