ERDC/CRREL TR-19-23

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Landform Assessment of Soil Strength from In-situ Experiments (LASSIE)

Preliminary Assessment of Landform Soil Strength on Glaciated Terrain in New Hampshire

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Abstract

Accurate terrain characterization is important for predicting off-road vehicle mobility. Soil strength is a significant terrain characteristic affecting vehicle mobility. Collecting soil strength measurements is laborious, making in-situ observations sparse. Research has focused on providing soil strength estimates using remote sensing techniques that can provide large spatial and temporal estimates, but the results are often inaccurate. Past attempts have quantified the soil properties of arid environments using landform assessments; yet many military operating environments occupy high latitude regions with landscapes dominated by glacial deposits. This study took preliminary strength measurements for glacial landforms deposited from the Laurentide Ice Sheet in New England. A range of common glacial landforms were sampled to assess shear strength, bearing capacity, and volumetric moisture content. Glacial outwash landforms had the highest average shear strengths, glacial deltas the lowest. There was a significant negative correlation between silt content and shear strength of the soil, a significant positive correlation between bearing capacity and clay content, and a significant negative correlation with sand content. Moisture content of soils was inversely correlated to the abundance of gravel in the deposit. This work provides initial insight to this approach on glaciated terrain, but continued sampling will provide more robust correlations.

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Preface

This study was conducted under a Congressional Add titled, "Landform Assessment of Soil Strength from In-situ Experiments (LASSIE)." The technical monitor was Dr. Sally Shoop.

The work was performed by the Terrestrial and Cryospheric Sciences Branch (TCSB) and the Force Projection and Sustainment Branch (FPSB) of the Research and Engineering Division, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication John Weatherly was the Acting Chief of TCSB; Jimmy Horne was Chief, CEERD-RR. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg and the Director was Dr. Joseph L. Corriveau.

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COL Teresa A. Schlosser was Commander of ERDC, and Dr. David W. Pittman was the Director.

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1 Introduction

1.1 Background

Accurate terrain characterization is of great importance to military operations, especially for assessing off-road vehicle mobility. Due to a lack of in-situ observations in many regions, it has become increasingly important to characterize terrain through remote sensing techniques. Many techniques use data gathered from visible or infrared satellite observations to develop geospatial products such as: vegetation, soil type, soil moisture, and land usage, all of which have notable effects on vehicle mobility. Unfortunately, these products only characterize the surface of the earth, leaving crucial information about the internal soil properties unknown. In addition to this, the accuracy of these results is often low when validated with field observations.

Geomorphological processes form the very basis of soil formation and development; once these processes and the landforms are understood, they can provide insight into the currently unknown internal soil properties. Previous studies have attempted to link landforms with soil characteristics (Harden 1982, McDonald et al. 2013, Shoop et al. 2018). However, these efforts were mainly focused on desert aeolian and alluvial landforms. These studies helped to provide a basic framework that could be applied to different types of landforms in desert environments.

However, many military operating environments are located in high latitude, austere regions, which are dominated by glacial terrain. These areas were covered by kilometer-thick ice sheets during the Last Glacial Maximum (LGM) approximately 26.5 – 20 ka (Clark et al. 2009). During this time period, continental sized ice sheets covered most of northern North America and large portions of northern Europe. As these ice sheets scoured the land and consequently retreated, they left behind many depositional landforms that dominate the surface today. Those trained in glacial geomorphology can use remotely sensed data to identify depositional landforms in areas that were previously glaciated. Each glacial landform has a distinct internal structure based on the manner of deposition. Thus, understanding what deposits are commonly associated with each landform will help provide insight into their internal soil properties.

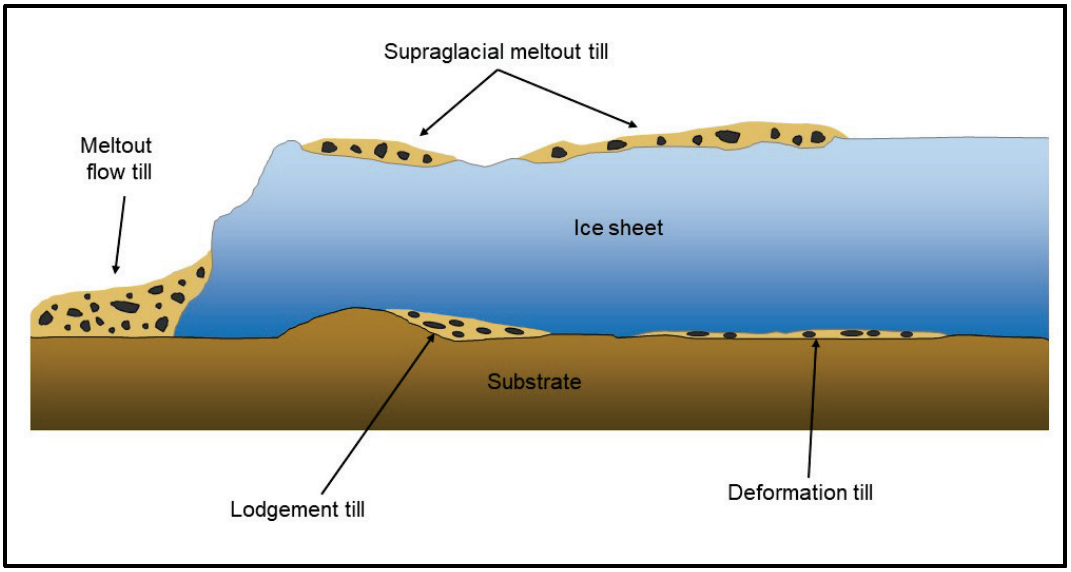
1.2 Glacial soils

Of glacial soils, till is perhaps the most common sediment that can be found in glaciated environments. It commonly displays a bimodal grain-size distribution, but often contains sediments ranging from clay size particles (~0.001 mm), to boulders (200 mm) (Benn and Evans 2014). The bimodality is a direct result of the two main entrainment mechanisms, abrasion (Hallet 1979) and quarrying (Iverson 2012). In addition to the varying grain sizes, till can also display different internal fabrics that may affect its overall strength. The internal fabric of till depends primarily on its mechanism of deposition, and can be classified into one of three main categories (see Figure 1):

1. Lodgment till, which is sediment that has been deposited by plastering of glacial debris from a sliding glacier bed.
   - Lodgment till is subject to the greatest amount of compaction and shearing.
   - Its parent material is typically sourced farther away.
2. Deformation till, which is sediment that has been disaggregated and homogenized by shearing in the subglacial deformed layer.
   - Deformation till has undergone gravitational compaction and shearing, but less so than lodgment till.
   - Its parent material is typically sourced locally.
   - Deformation till displays similar engineering properties to lodgment till.
3. Melt-out till, which is released by melting of stagnant or slowly moving debris-rich glacier ice and is deposited without subsequent transport or deformation. Melt-out till is split up into subglacial melt-out till (melting of debris-rich ice at the bottom of the glacier) and supraglacial melt-out till (melting of ice on the glacier surface).
   - Melt-out till is only subject to gravitational compaction, no shearing.
   - Melt-out till is more variable than lodgment or deformation till and can contain glaciofluvial sediments.

Several studies have attempted to characterize the engineering properties of glacial tills using laboratory experiments (Atkinson et al. 1985, Chegini and Tretner 1996, Iverson et al. 1996, Bell 2002), and in-situ field measurements (McKinlay et al. 1974, Clarke 2018). One of the main takeaways from these studies was that the engineering properties of till can vary drastically between deposits due to their heterogeneous nature.

Figure 1. Schematic diagram of the main types of glacial till and their mechanisms of deposition.



Clarke (2018) found that the shear strength associated with these till deposits were strongly correlated to the concentration of fine-grained particles in the deposit. Tills with larger amounts of fine-grained particles (>15%) had engineering properties significantly different from deposits that were dominated by coarse-grained material. Another distinct factor that affects the engineering properties was the way the tills were deposited (i.e., lodgment, deformation, melt-out) (Clarke 2017). Most previous work however, focused on till deposits, which are only one of the sediment types that are commonly associated with glacial landscapes.

In addition to glacial tills, other common surficial deposits in glaciated terrain include glaciolacustrine and glaciofluvial deposits. These deposits have similarities with the non-glacial fluvial and lacustrine environments. Glaciofluvial deposition is generally like fluvial sedimentation with the main difference being that the water is generally colder and denser in glaciofluvial environments so suspended particles will have different transport distances (i.e., particles can travel further before deposition) (Benn and Evans 2014). Similarly, glaciolacustrine and lacustrine deposition occur in a comparable manner. Suspended particles settle out of the water column and get deposited in horizontal layers on the lakebed. The main difference being that, in the glaciolacustrine environment, grain-size in the deposit can fluctuate significantly based on the amount of meltwater input (Benn and Evans 2014).

1.3 Objective

The primary objective of this work was to provide preliminary insight into relationships between glacial landforms and both their surficial and internal soil strength properties. With this relationship, soil strength can be more accurately quantified using remotely sensed data and therefore can help provide a more accurate representation of the terrain. Instead of focusing solely on glacial tills, this work deliberately sampled from an array of landforms that display the main surficial deposits that are found in glaciated terrain.

1.4 Approach

To accomplish these objectives, researchers at the U.S. Army Engineer Research and Development Center's Cold Regions Research and Engineering Laboratory collected measurements on soil strength and soil properties across a range of glacial geomorphic landforms in central and northern New Hampshire. New England has long been the focus of glacial-geologic studies (Ridge and Toll 1999, Thompson et al. 1999, Balco et al. 2002, Balco et al. 2009, and Ridge et al. 2012) due to the abundance and variety of glacial depositional landforms covering the landscape. Thus, it provided an ideal location for conducting this analysis.

2 Methodology

2.1 Sampling locations

Sampling for this study was conducted over a 2-day period, with each day focusing on a different region of NH (Figure 2). The first day focused mainly on the Connecticut River Valley (CRV) region near Hanover, NH. Sites in this region are mainly located off NH Routes 4 and 10. The second day focused on the Littleton-Bethlehem (LB) region, north of Franconia North State Park. These sites were primarily located at active sand and gravel quarries off NH Route 302. Table 1 lists the locations, landform type, descriptions, and soil texture classifications for each field site tested in this study. Each field site was labeled with "NH" and a number (i.e., NH04). In cases where multiple samples were taken at one site, a letter was added to the sample naming scheme (i.e., NH03a).

Figure 2. Clockwise from top left. Locator map showing CRV and LB locations in New Hampshire, field sites, and associated landform types for CRV and LB areas.

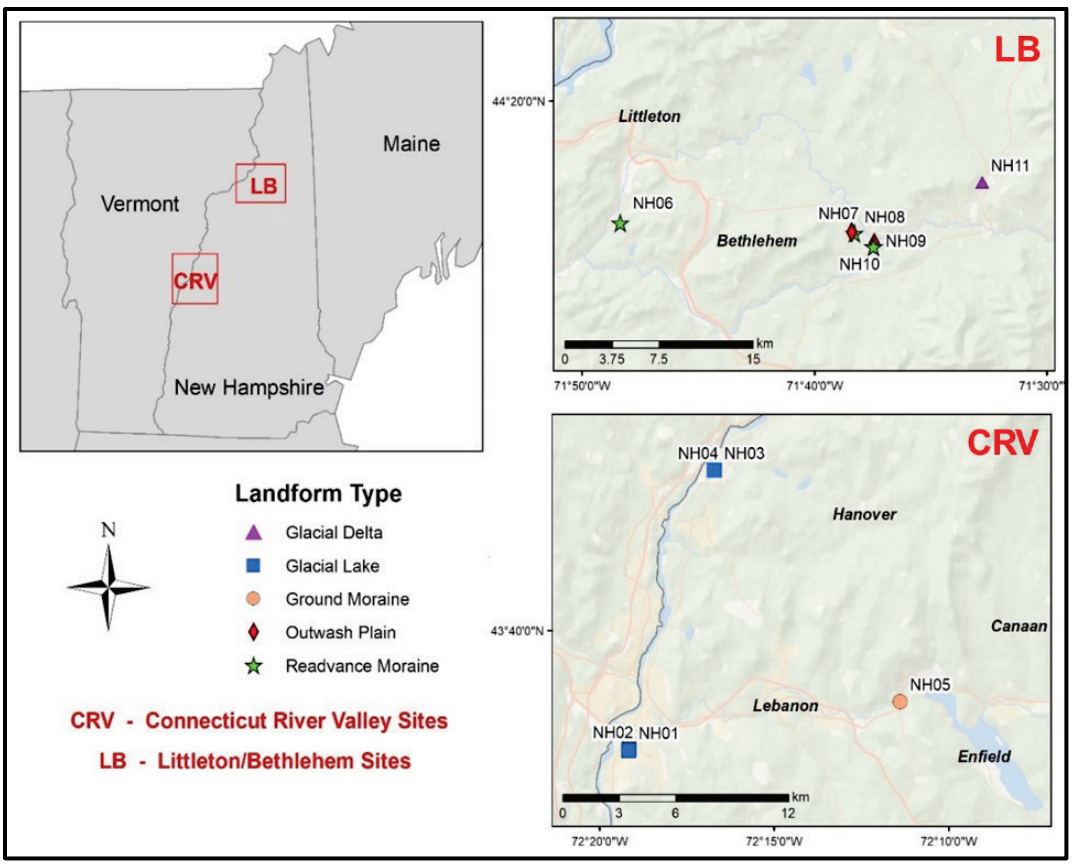


Table 1. Field site information including coordinates, landform type, site description, and Unified Soils Classification System (USCS) soil classification.

Sample ID	Date	Latitude	Longitude	Landform	Description	USCS Class*
NH01	9/5/2018	43.62692	-72.31934	Glacial Lake – Summer Layer	Glacial Lake Hitchcock varve section – proximal summer layer	SP
NH02	9/5/2018	43.62709	-72.31920	Glacial Lake – Winter Layer	Glacial Lake Hitchcock varve section – proximal winter layer	ML
NH03a	9/5/2018	43.71975	-72.27858	Glacial Lake – Summer Layer	Glacial Lake Hitchcock varve section – distal summer layer	SM
NH03b	9/5/2018	43.71975	-72.27858	Glacial Lake – Winter Layer	Glacial Lake Hitchcock varve section – distal winter layer	CL
NH04	9/5/2018	43.71980	-72.27827	Glacial Lake – Winter Layer	Glacial Lake Hitchcock varve section – distal winter layer	CL
NH05	9/5/2018	43.64299	-72.18983	Ground Moraine	Mascoma glacial melt-out till, subangular clasts in predominantly silt matrix	GC
NH06	9/6/2018	44.27326	-71.80571	Readvance Moraine	LB readvance moraine over bedrock; lodgment till containing sub-rounded clasts with predominantly silt/sand matrix	GM
NH07	9/6/2018	44.26817	-71.63808	Readvance Moraine	LB readvance moraine over outwash deposit; lodgment till with rounded clasts in predominantly sand matrix	GM
NH08	9/6/2018	44.26866	-71.63993	Outwash – Sand	Sandy outwash deposit under LB moraine; contains visible bedding planes	SP
NH09	9/6/2018	44.26157	-71.62444	Readvance Moraine	LB readvance moraine over outwash deposit; lodgment till containing sub-rounded clasts with predominantly silt/clay matrix	GC
NH010a	9/6/2018	44.26326	-71.62376	Outwash – Sand	Sandy outwash deposit under LB moraine; contains visible bedding planes	SP
NH010b	9/6/2018	44.26326	-71.62376	Outwash – Gravel	Gravel-rich outwash deposit under LB moraine; contains visible bedding planes	GP
NH011	9/6/2018	44.2932	-71.54628	Glacial Delta	Foreset beds of glacial delta; climbing ripples and large waveforms abundant	SM

* CL = lean clay; GC = clayey gravel; GM = silty gravel; GP = poorly graded gravel; ML = Lean silt; SM = silty sand; SP = poorly graded sand

Each field site was selected by ERDC-CRREL Research Geologist Taylor Hodgdon and New England glacial geology expert Woodrow Thompson (Thompson et al. 2017). In addition to accessibility, sites were selected to provide the best representations of common glacial landforms (Table 2). Some of the sampled sites were in active sand and gravel quarries, thus these sites typically have fewer measurements.

Table 2. Glacial landforms sampled in this study with accompanying descriptions of their deposition.

Landform	Description
Readvance Moraine	Accumulation of lodgment till carried or deposited by a glacier. The material, which ranges in size from boulders to sand and clay, is unstratified when dropped by the glacier and shows no sorting or bedding.
Ground Moraine	Consists of an irregular blanket of melt-out or lodgment till deposited under a glacier. Composed mainly of clay and silt, it is the most widespread deposit of continental glaciers.
Glacial Lake (summer and winter layers)	Sedimentary deposits that form at the margins of glaciers where water has been dammed to form proglacial lakes. Sediments in the bedload and suspended load are carried into lakes and deposited, both of which are typically well sorted. The bedload (coarser grained material–coarse sands) is deposited during the summer months when large amounts of meltwater pulse out of the glacier, while the suspended load (finer grained material – silt and clay) is deposited during the winter months.
Glacial Delta	Forms from deposition of sediment that is carried by a river into a glacial lake. The flow velocity of water decreases as it exits the river and enters an unconstrained body of water. This causes medium grained sediments to be deposited in shallow sloping or highly angular bedding planes.
Outwash Plain (sand plains and gravel channels)	Expansive deposits of sand and gravel carried by running water from the melting ice of a glacier and laid down in stratified deposits. Coarser grained sands and gravels are deposited proximal to the glacier margin and finer grained sands and silts are deposited distally.

2.2 Landform soil measurements

Sampling in the CRV region took place on September 5th, 2018, which was a partly cloudy day in the low 80s °F. Sampling in the LB region took place the following day (September 6th), which was in the mid-70s °F, with scattered thunderstorms throughout the day. Figure 3 shows temperature and precipitation measurements starting 5 days before sampling. The shear strength and bearing capacity (where appropriate) were measured at each landform site to gauge the strength of the soil, and volumetric moisture content was recorded at all sites where the probe could be inserted. A rough visual grain-size analysis was conducted by approximating the percent weight of gravel, sand, silt, and clay in a 1 m^2 area to determine the most representative USCS classification (Table 3). Figure 4 shows examples of the internal structure of each landform.

Figure 3. Temperature and precipitation trends for CRV and LB sites beginning 5 days before field measurements (data collected from wunderground.com).

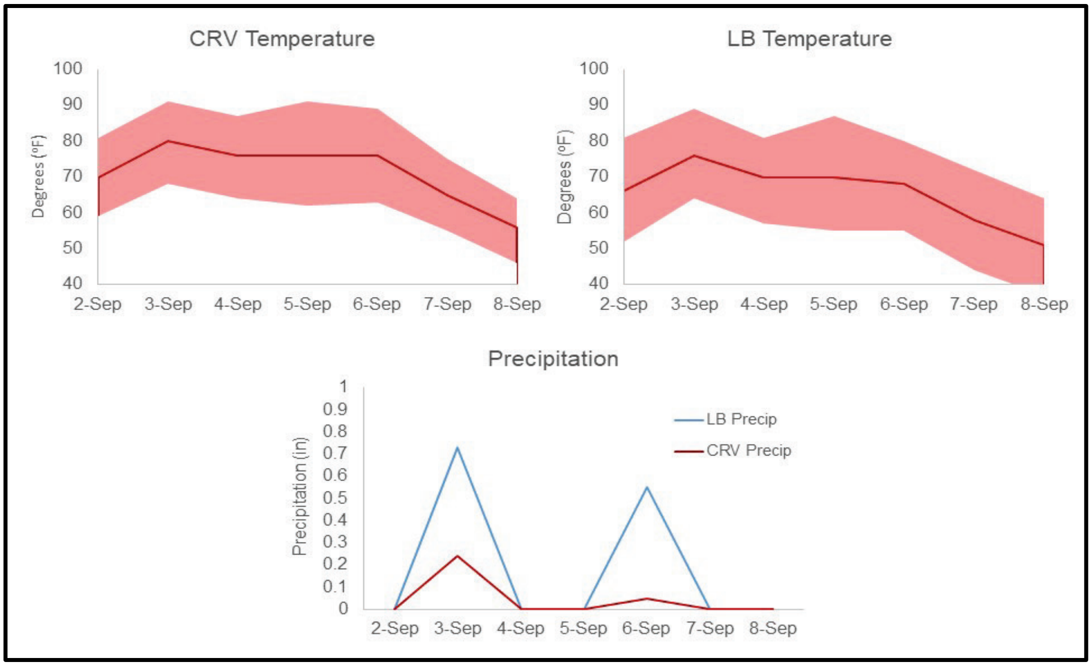
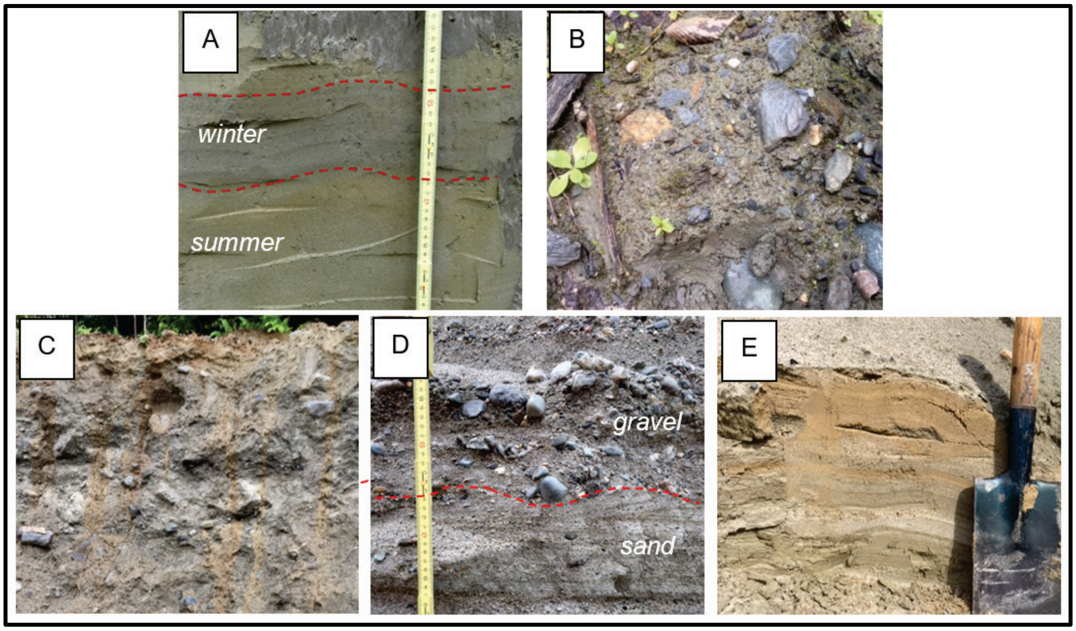


Table 3. Results of visual grain-size analysis for each field site.

Site	Gravel	Sand	Silt	Clay
NH01	0%	70%	20%	10%
NH02	0%	10%	20%	70%
NH03a	0%	50%	30%	20%
NH03b	0%	10%	20%	70%
NH04	0%	0%	30%	70%
NH05	50%	10%	10%	30%
NH06	50%	20%	20%	10%
NH07	50%	20%	30%	0%
NH08	0%	90%	10%	0%
NH09	50%	10%	10%	30%
NH010a	60%	30%	10%	0%
NH010b	0%	80%	10%	10%
NH011	0%	60%	30%	10%

Figure 4. Example photos of the internal structure for each landform tested in this study: (A) glacial lake varves (alternating horizontal layers of sands and silt/clay), (B) ground moraine (unconsolidated deposits of angular clasts in fine-grained matrix), (C) readvance moraine (lodgment till composed of clasts plastered in matrix of silty sand), (D) outwash deposit (large layers of well sorted sand with lenses of rounded gravel from channel deposits), and (E) glacial delta (well sorted layers of sands and silts deposited in horizontal or low angle bedding planes).



2.2.1 Shear vane

Internal shear strength measurements were made using a H60 Field Inspection Shear Vane Tester (shear vane). To collect a measurement, the shear vane is inserted into the soil until the entire vane head is covered, then a turning force is applied by hand until the soil shears (the shear vane slips when this occurs). The maximum shear force is recorded on the instrument in kilopascals. Several vane sizes are available for the shear vane, but this study used the 15 mm (small) diameter and the 20 mm (medium) diameter vanes depending on the material being sampled. Values for the medium diameter shear vane can range from 0-200 Kpa. Shear strength values were recorded for each site, except for NH02 where the shear vane could not be inserted into the soil. Average shear strength measurements were calculated for landforms that had multiple shear vane measurements.

2.2.2 Clegg impact hammer

The Clegg Impact Hammer (Clegg) consists of a drop hammer operating within a vertical guide tube (Clegg 1980, ASTM 2016). The hammer is commonly used to test the hardness of turf fields, unpaved roads, or road sub-base, but can also be used to measure the stiffness of natural soils. The drop hammer is manually raised to a set height and then dropped until it meets the surface. An accelerometer is attached to the hammer and a digital readout records the hammer's deceleration. The hammer is dropped four times at each sampling location, and deceleration readings are recorded for each drop. The 2.25 kg Clegg was selected to measure the soil bearing capacity at the sites in this study.

Clegg measurements were taken at sites where a horizontal surface could be cleared. Surfaces were manually cleared while attempting to minimize disturbance to the soil structure beneath, however some disturbance likely took place. The sample sites include: NH03, NH04, NH05, NH09, and NH11. The other sites were in regions where no flat surface was able to be cleared for testing. Clegg Impact Values (CIVs) for each site were taken as the measurement of the third drop for the 2.25 kg Clegg. Typically, the CIV reading will increase with each drop as the ground is further compacted, which is why the third drop is selected. This pattern was observed in CIV measurements during our field campaign. CIV values were converted to California Bearing Ratios (CBR) following equation (1) for the 2.25 kg Clegg data (Shoop et al. 2012, Millar 1977).

$$CBR(\%) = e^{\frac{10CIV_{2.25kg} - 14.986}{79.528}} \tag{1}$$

2.2.3 Field Scout volumetric moisture content

A Field Scout TDR 300 moisture meter was used to measure volumetric water content at sites NH04 and NH06-NH11. The other sites were not measured as the soil would not allow the probe to be fully pushed into the surface. The meter calculates volumetric water content by measuring conductivity between two rods. The 4 cm long rods were used at sites where moisture readings were collected. Volumetric moisture values for each site were recorded; for landforms with multiple readings, the average of all measurements was recorded.

3 Results and Discussion

3.1 Soil strength and moisture variations with landform

Tables 4 and 5 list the average shear strength and bearing capacity for each landform. Glacial lake landforms were further broken down into "summer layer" and "winter layer" subcategories as they displayed drastically different soil textures from one another, thus their strengths may differ as well. The summer and winter naming comes from the season in which the varve layers were originally deposited in the glacial lake: summer, when large amounts of meltwater and coarse-grained sediment pulse out of the base of the ice sheet, and winter, when little meltwater, and small amounts of fine-grained sediment exit out of the base of the ice sheet. Due to the lower turbidity from reduced meltwater, the finer particles can settle out of the water column. Outwash landforms were subcategorized as gravel – channel deposits, and sand – plain deposits.

Table 4. Average (±1 std) shear vane measurements for each sampled glacial landform. Glacial Lake and Outwash landforms broken down into subcategories.

Landform	Number of Samples	Average Shear Vane (kPa)
Glacial Lake – Summer layer	14	42.0 ±27.9
Glacial Lake – Winter layer	10	50.0 ±17.1
Ground Moraine	6	41.7 ±34.2
Readvance Moraine	9	57.4 ±24.9
Outwash Plain – Gravel	5	58.0 ±10.2
Outwash Plain – Sand	10	70.7 ±40.3
Glacial Delta	14	17.4 ±4.7

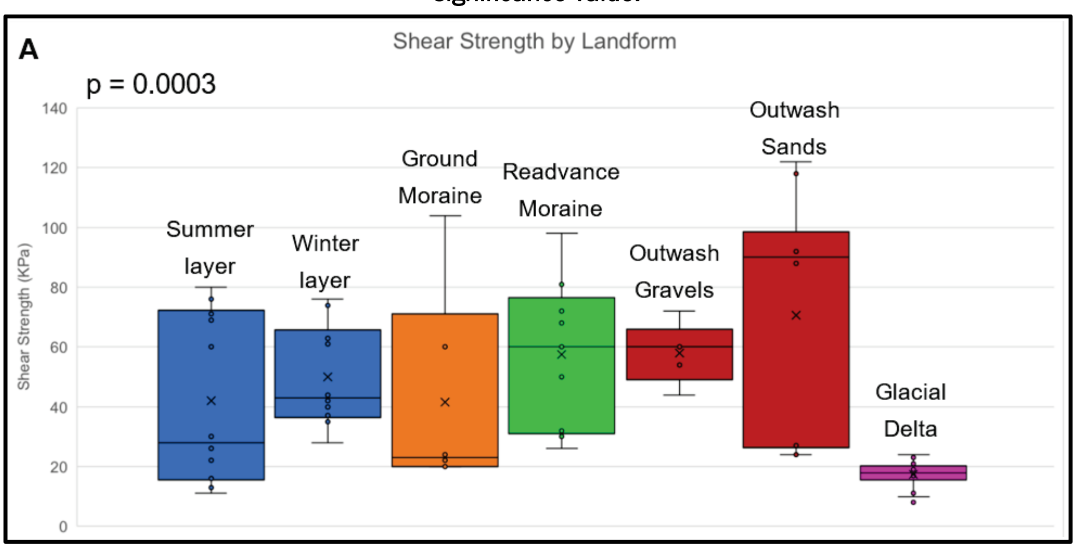
Table 5. Average (±1 std) CIV and CBR measurements for each sampled glacial landform. Glacial lake landform broken down into subcategories. No measurements were taken for outwash deposits.

Landform	Number of samples	Average CIV	Average CBR
Glacial Lake – Summer layer	1	5.6 ±NA	1.7 ±NA
Glacial Lake – Winter layer	1	12.4 ±NA	3.9 ±NA
Ground Moraine	2	8.1 ±1.0	2.3 ±0.3
Readvance Moraine	2	6.9 ±4.7	1.7 ±1.2
Glacial Delta	7	6.7 ±2.9	2.6 ±1.5

A Kruskal-Wallis one-way analysis of variance (Kruskal and Wallis 1952) was conducted for shear strength measurements to see how significantly different the strengths were between landforms. Figure 5 shows the p-values and box plots for the shear strength measurements. The Kruskal-Wallis test indicates that the shear strengths associated with each landform are significantly different from one another ($p < 0.5$). The sandy outwash plain sediments had the greatest average shear strength, but also had the largest variability. The gravel outwash and readvance moraine had the next highest shear strengths, but with smaller variability than the sandy outwash. The glacial lake sediments and ground moraine had intermediate shear strengths, with the winter layer being the highest of the three and having the smallest variance. The glacial delta had both the lowest shear strength and smallest variance of any landform.

The ground moraine and the readvance moraine had some of the largest variations in shear strength (±34.2 and ±24.9) of the sampled landforms. This can be explained by the fact that these deposits are composed of lodgment and melt-out till, which have the widest grain-size distributions of the sampled landforms. Thus, the measurements are likely to vary, even within the same landform. In contrast, the delta, winter varve layers, and outwash-gravel deposits are all well sorted, which can explain the smaller variance in shear measurements (±4.7, ±17.1, and ±10.2). The summer varve layers and outwash sands also had notably high variations in shear strength (±27.9 and ±40.3), however these deposits are also well sorted. The wide variation may stem from density differences or the varying moisture contents. These deposits are primarily composed of sand, which is weakly cohesive when dry. However, if the soil is wet, the cohesion can be greater thereby increasing the strength (Kemper and Rosenau 1984).

Figure 5. Box plot of shear strength measurements by landform; p = Kruskal-Wallis significance value.



Sampling with the 2.25 kg Clegg was sparse and thus some landforms only have 1-2 measurements, while others have none. With so few data points, it is hard to draw any definitive conclusions about the landforms relation to soil bearing capacity. Instead, average CBR values for each landform were compared to typical undisturbed (natural) soil and altered (engineered) soil ranges for the associated USCS soil classes (Table 6). The only landforms with a CBR value that fit within the common undisturbed ranges were the glacial lake winter varve layer (CBR between 2-48), and the glacial delta (CBR between 3-100, when including associated uncertainty). All other landforms had CBR values that were significantly smaller than the typical undisturbed and altered ranges, even when considering their uncertainty. These uncharacteristically low values may be a result of the clearing that had to take place to have a horizontal surface that could be sampled from. Even though attempts were made to minimize the disturbance of the underlying soil, it was likely weakened.

Table 6. Typical CBR ranges for USCS classes (Undisturbed soils – Shoop et al. 2008, Altered soils – Fang 1991). Ranges match ordering of USCS Class.

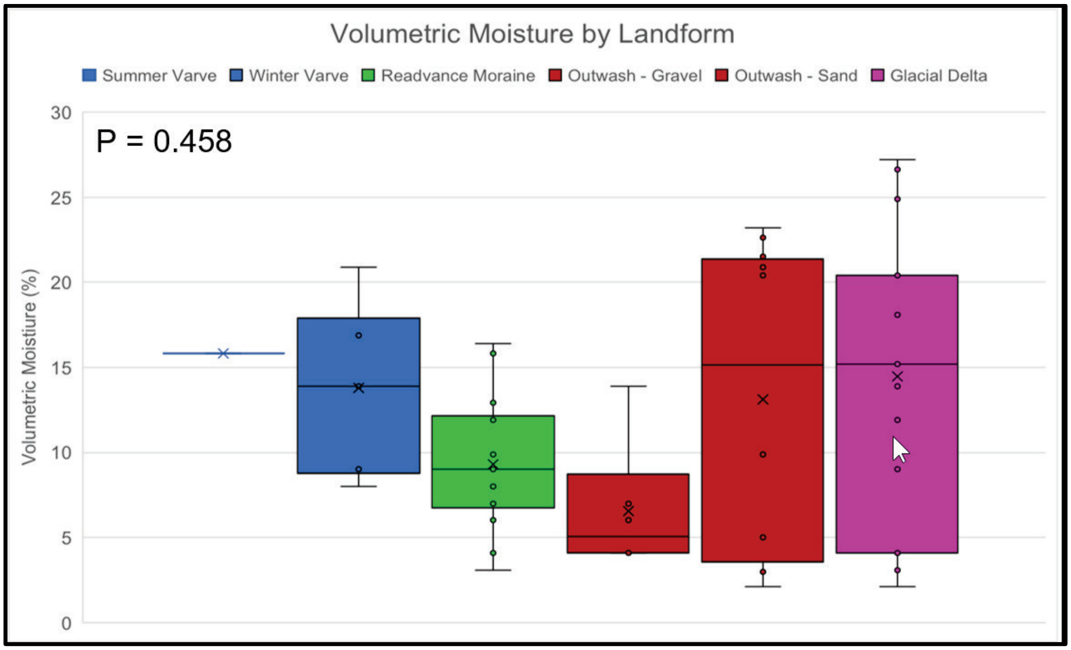
Landform	USCS Class	Measured Average CBR	Undisturbed CBR Ranges	Altered CBR Ranges
Summer layer	SP/SM	1.7 ±NA	NA / 7 – 73	10 – 25 / 10 – 40
Winter layer	ML/CL	3.9 ±NA	6 – 37 / 2 – 48	5 – 15 / 5 – 15
Ground Moraine	GC	2.3 ±0.3	31 – 100 / 5 – 100	20 – 80 / 20 – 40
Readvance Moraine	GM/GC	1.7 ±1.2	31 – 100 / 5 – 100	20 – 80 / 20 – 40
Outwash – Gravel	GP	-	NA	25 – 60
Outwash – Sand	SP	-	NA	10 – 25
Glacial Delta	SM	2.6 ±1.5	3 – 158 / 7 – 73	10 – 20 / 10 – 40

Table 7 lists the average volumetric moisture content for each landform. A Kruskal-Wallis analysis was also conducted for the volumetric moisture values (Figure 6). The Kruskal-Wallis test indicated that there was no significant difference in volumetric moisture measurements between landforms. Even though there was roughly 0.5 in. of rain at the LB field area on the day of sampling, compared to the 0 in. at CRV the day prior, there was no noticeable increase in volumetric moisture content of the landforms measured that day.

Table 7. Average (±1 std) volumetric moisture measurements for each sampled glacial landform. Glacial Lake and Outwash landforms broken down into subcategories.

Landform	Number of Samples	Average Volumetric Moisture (%)
Glacial Lake – Summer layer	2	15.8 ±0.0
Glacial Lake – Winter layer	6	13.8 ±4.8
Ground Moraine	0	–
Readvance Moraine	22	9.3 ±3.8
Outwash Plain – Gravel	6	6.5 ±3.8
Outwash Plain – Sand	12	13.1 ±9.0
Glacial Delta	15	14.5 ±8.6

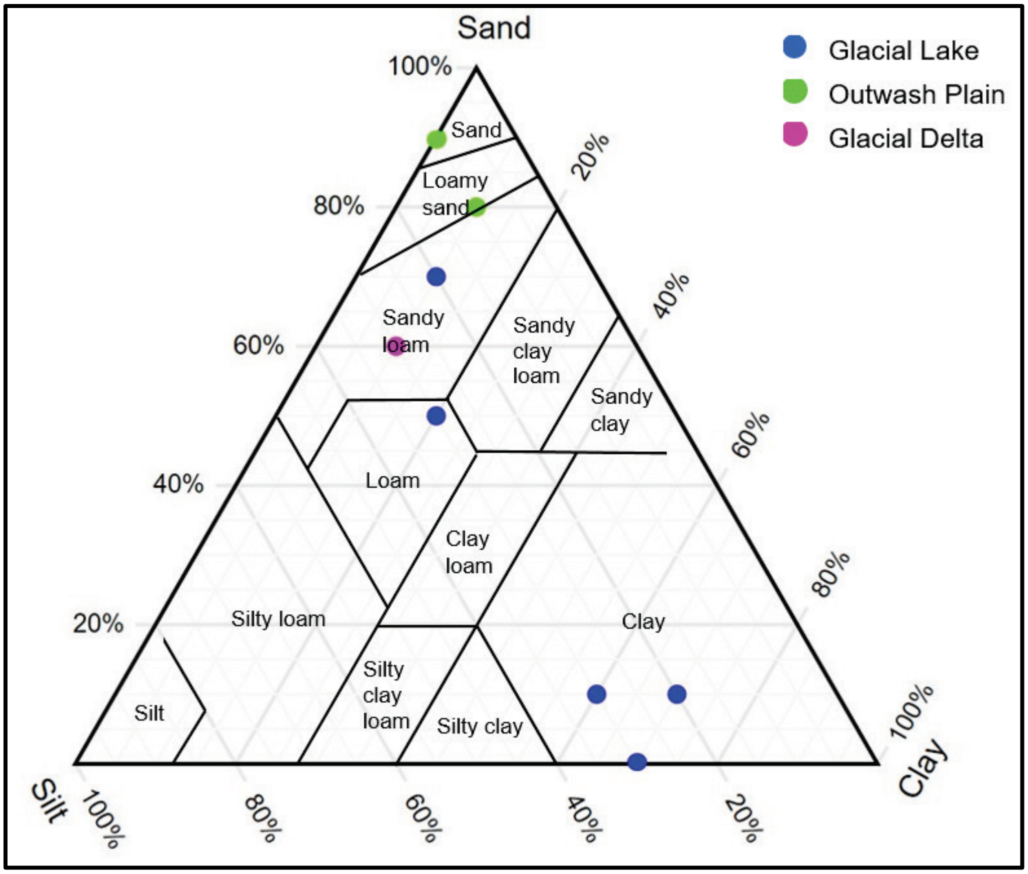
Figure 6. Box plot of volumetric moisture measurements by landform.



3.2 Landform soil texture relation to strength properties

The landforms sampled in this study covered a wide range of soil compositions, which is common for glacial environments. In addition to the USCS soil classes that were assigned to each landform, a U.S. Department of Agriculture (USDA) soil texture (Figure 7) was also assigned, when appropriate, to see how the classifications varied. These estimates are based on the percent composition of the sand, silt, and clay particles. Glacial lake landforms were concentrated in two clusters; one well within the USDA clay class and the other in loam/sandy loam classes. Again, due to the presence of two distinctly different soil textures, this landform was split into summer and winter layers for comparison. The three outwash plain landforms had the highest concentrations of sand.

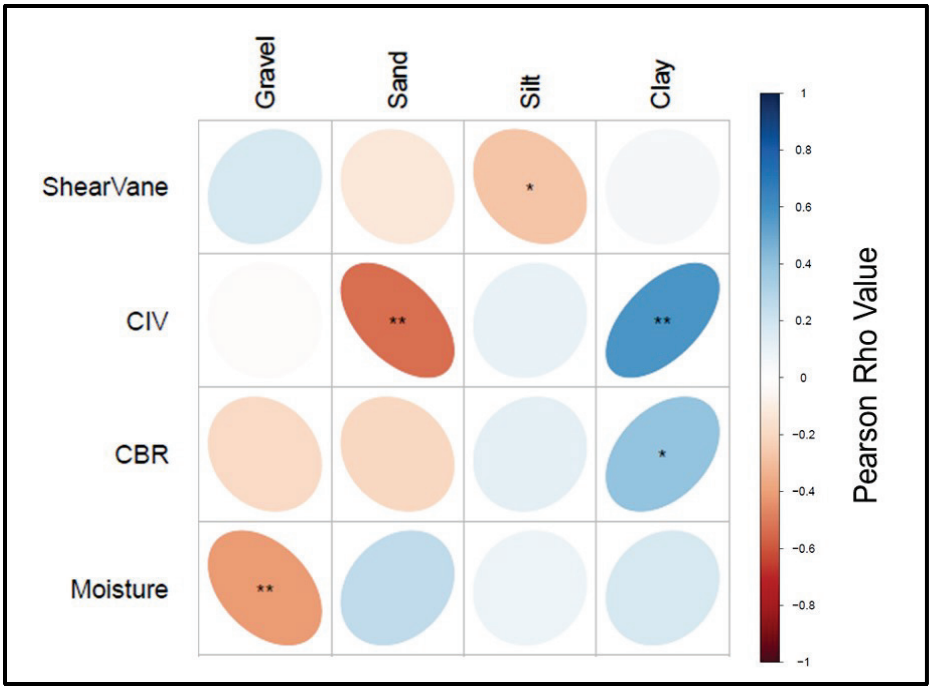
Figure 7. Ternary plot of USDA classified surface soil textures.



However, it is important to note that site NH10b had over 50% gravel while the other two outwash sites (NH8 and NH10a) had less than 5%, once again leading to subclassifications of sand plains and gravel channels for that landform. The one glacial delta that was sampled was classified as a sandy loam. It is evident that USDA classifications do not accuratley represent the engineering properties of many of these soils (especially the till deposits) as gravel is a significant component that is not considered in this texture scheme. Thus, the landforms with significant gravel contents (>50%) were not plotted on the USDA ternary. Instead, these landforms would have texture classifications as follows: ground moraines = gravelly silty loam, readvance moraines = gravelly loamy sands, and the gravel outwash deposit = extremely gravelly loamy sand (Schoeneberger et al. 2012).

A Pearson correlation matrix was generated to see if there were any distinct relationships between the abundance of each grain-size in a sample and its strength parameters. Since there was a large abundance of gravel in many of the deposits, a comparison was conducted using USCS classifications, not using the USDA normalized fine grain sediments (Figure 8).

Figure 8. Pearson correlation matrix showing Rho values defined between soil properties and surface textures (* is p<0.05 and ** is p<0.01),



The Pearson correlation matrix shows a strong negative correlation between sand and CIV (p <0.01), while clay appears to be strongly positively correlated to both CIV (p <0.01) and CBR (p <0.05). The shear strength of the landforms appears to be slightly negatively correlated to the percentages of silt in the deposits. Volumetric moisture contents also do not seem to have a strong correlation to the soil textures except for gravel where there is a strong negative correlation.

The positive correlation between clay content and CIV/CBR is likely because clay is highly cohesive, therefore it typically has a high bearing capacity, unless wet (Day 1992). The negative correlation between sand and CIV highlights the fact that dry sands, unlike clay, have very low cohesion and therefore a low bearing capacity (Bell 2013). Gravels are considered well-drained soils, which explains the negative correlation between gravel abundance and volumetric moisture content. The negative correlation between silt and shear strength however is not as intuitive. Silt soils have a low porosity, which allows them to retain water for longer periods of time (Bell 2013). The ground moraine had the highest silt content (~50%). This landform was not sampled for volumetric moisture content, but there was water noticeably seeping out of the deposit, indicating it was fully saturated. This could explain the negative correlation observed between these two parameters.

4 Conclusions and Future Work

The overall purpose of this work was to provide preliminary results of the internal soil properties of glacial landforms. In addition to samples from till-rich landforms, this study provides some of the first soil strength measurements of non-till related deposits. Initial measurements indicate:

- The shear strengths of the glacial landforms are statistically significantly different from one another when using the Kruskal-Wallis test.
- Overall, both the sand and gravel outwash deposits had the largest mean shear strengths, while glacial deltas had the lowest.
- The CIV was positively correlated to the clay content and was negatively correlated to the abundance of sand in the deposit.
- The only landforms for which calculated CBR values fit within the common natural ranges for the associated USCS soil classes were the winter varve layer and the glacial delta. All other landforms had CBR values that were significantly lower than the typical ranges for either natural soils or engineered soils.
- Overall, the outwash plains have the highest concentration of sand compared to the other landforms, while the winter layers of the glacial lake deposits have the largest concentration of clay.
- The percentage of gravel, sand, and clay in each landform did not seem to have any noticeable effect on the shear strength of the landform, while there was a slight positive correlation between shear strength and silt content.
- The moisture content of soils was inversely correlated to the abundance of gravel in the deposit.

While this study resulted in a unique look at the relationship between glacial landforms and soil strength, it will be important for future studies to collect significantly more strength and moisture measurements, to build a more statistically meaningful dataset. Glacial landforms from a more widely dispersed geographic areas should also be sampled. One aspect that was not considered in this study was the dominant parent material that made up the deposits. Different types of rocks have varying hardness properties that can contribute to the overall strength of the deposit they are found in. All the sites sampled in this study were stratigraphic cross sections, which made taking bearing capacity measurements quite difficult. In the future, it will be important to locate sites where there are natural surfaces that can be sampled using a Clegg or other tools to measure bearing capacity such as a Dynamic Cone Penetrometer. It will also be crucial to minimize any disturbance in these surfaces to ensure that the bearing capacity readings are accurate. Vegetation can also have a strong impact on the surface strength of soil, thus in future studies it will be important to sample from both vegetated and non-vegetated landforms that are in an undisturbed state.

To produce viable strength datasets using geomorphological mapping techniques, it will be increasingly important to provide validation through measurements in the field. In the future, more robust grain-size analyses should be conducted to provide more accurate classifications for the soil types of each landform and to validate visual grain-size analyses conducted in this study. While this work provided preliminary insight into the efficacy of this approach on glacial landforms, the collection of more measurements along with a thorough analysis of the physical process that could impact strength will help improve our understanding of the landforms impact on soil strength.

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Acronyms and Abbreviations

Term	Definition
ANSI	American National Standards Institute
ANZ	Australian-New Zealand
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CI	Cone Index
CIV	Clegg Impact Value
CL	Lean Clay
CRREL	Cold Regions Research and Engineering Laboratory
CRV	Connecticut River Valley
ERDC	U.S. Army Engineer Research and Development Center
FPSB	Force Projection and Sustainment Branch
GC	Clayey Gravel
GM	Silty Gravel
GP	Poorly Graded Gravel
GW	Well-Graded Gravel
ID	Identification
ka	Kilo-annum (1000 years ago)
LASSIE	Landform Assessment of Soil Strength from In-situ Experiments
LB	Littleton-Bethlehem
LGM	Last Glacial Maximum
LIS	Laurentide Ice Sheet
ML	Silt
NA	Not Applicable
NSN	National Supply Number
OMB	Office of Management and Budget
SAR	Same As Report
SC	Clayey Sand
SF	Standard Form
SM	Silty Sand
SP	Poorly Graded Sand
SW	Well-Graded Sand
TCSB	Terrestrial and Cryospheric Sciences Branch
TR	Technical Report
USCS	Unified Soil Classification System
USDA	U.S. Department of Agriculture

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
square miles	2.589998 E+06	square meters
miles (U.S. statute)	1,609.347	meters

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14. ABSTRACT
Accurate terrain characterization is important for predicting off-road vehicle mobility. Soil strength is a significant terrain characteristic affecting vehicle mobility. Collecting soil strength measurements is laborious, making in-situ observations sparse. Research has focused on providing soil strength estimates using remote sensing techniques that can provide large spatial and temporal estimates, but the results are often inaccurate. Past attempts have quantified the soil properties of arid environments using landform assessments; yet many military operating environments occupy high latitude regions with landscapes dominated by glacial deposits. This study took preliminary strength measurements for glacial landforms deposited from the Laurentide Ice Sheet in New England. A range of common glacial landforms were sampled to assess shear strength, bearing capacity, and volumetric moisture content. Glacial outwash landforms had the highest average shear strengths, glacial deltas the lowest. There was a significant negative correlation between silt content and shear strength of the soil, a significant positive correlation between bearing capacity and clay content, and a significant negative correlation with sand content. Moisture content of soils was inversely correlated to the abundance of gravel in the deposit. This work provides initial insight to this approach on glaciated terrain, but continued sampling will provide more robust correlations.

15. SUBJECT TERMS
Glacial landforms, New Hampshire, Shear strength of soils, Soil mechanics, Trafficability

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