ERDC/CRREL MP-20-4

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER

ERDC 6.2 Boreal Aspects of Ensured Maneuver (BAEM)

SnowMicroPenetrometer Applications for Winter Vehicle Mobility

T. Meehan, H. P. Marshall, E. Deeb, and S. Shoop

August 2020

ERDC 6.2 Boreal Aspects of Ensured
Maneuver (BAEM)

ERDC/CRREL MP-20-4
August 2020

SnowMicroPenetrometer Applications for Winter Vehicle Mobility

T. Meehan and H. P. Marshall

Department of Geosciences
Boise State University
1910 University Drive MS 1535
Boise, ID 83725-1535

E. Deeb and S. Shoop

U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

Draft Report

Prepared for Assistant Secretary of the Army for Acquisition, Logistics, and Technology
103 Army Pentagon
Washington, DC 20314-1000

Under Project 465395, ERDC 6.2 "Boreal Aspects of Ensured Maneuver (BAEM)," and Project 471941, "Remote Assessment of Snow Mechanical Properties" and "Mobility in Peat and Northern Soils"

Preface

This study was conducted for the Assistant Secretary of the Army for Acquisition, Logistics, and Technology under project number 465395, “Boreal Aspects of Ensured Maneuver (BAEM),” which is part of the U.S. Army Engineer Research and Development Center (ERDC) 6.2 Remote Assessment of Infrastructure for Ensured Maneuver (RAFTER) Program managed by Ms. Danielle Whitlow, ERDC Geotechnical and Structures Laboratory (GSL).

The work was performed by the Department of Geosciences, Boise State University and the Lidar and Wetlands Group of the Remote Sensing / Geographic Information System Center of Expertise (CEERD-RS) and the Force Projection and Sustainment Branch (CEERD-RRH) of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Elias Deeb was lead for the Lidar and Wetlands Group; Mr. David Finnegan was Chief, CEERD-RS; Mr. Jimmy Horne was Acting Chief, CEERD-RRH; and Mr. 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.

This Miscellaneous Paper (MP) was published as the following:

Meehan, T., H. P. Marshall, E. Deeb, and S. Shoop. 2019. “SnowMicroPenetrometer Applications for Winter Vehicle Mobility.” In *Proceedings of the 18th International Conference on Cold Regions Engineering and the 8th Canadian Permafrost Conference*, 18–22 August 2019, Quebec City, Quebec, Canada.

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

SnowMicroPenetrometer Applications for Winter Vehicle Mobility

T. Meehan, M.S.
Boise State University, Boise, Idaho, USA

H. P. Marshall, Ph.D.
Boise State University, Boise, Idaho, USA

E. Deeb, Ph.D.
Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, USA

S. Shoop, Ph.D.
Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, USA

ABSTRACT: The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) provides cold regions research and development in support of the US military and the nation. For winter military operations this support includes vehicle mobility modeling over snow. Many factors relate to vehicle performance, fuel efficiency and operation efficiency, including the vehicle specifications and the land surface conditions. Comprehending snow macromechanical characteristics – such as elastic modulus, stiffness, and strength – is critical in understanding how effectively a vehicle will travel over snow covered terrain. Vehicle instrumentation data (inertial measurement units and vehicle telemetry) and observations of the snow pack (both satellite and ground-based) are leveraged to improve the modeled index for winter vehicle performance. Currently, the available mobility models are physically-based and consider numerous factors related to cross country mobility such as slope, soil type, terrain strength, land classification and vegetation. The algorithms related to the impact of snow, however, are driven by snow depth and bulk snow density alone. This research deployed a SnowMicroPenetrometer (SMP) whose capabilities were expanded to measure several types of snow, including virgin snow, vehicle tracked snow and processed or groomed snow roads. The SMP high-resolution snow structural profiles show the value of the instrument as a tool for mobility studies. Correlation analysis was conducted between the SMP and Rammsonde penetrometer using median values from different snow types at a particular site. The data express a trend that rupture force, penetration force, density, strength, and ram hardness increases when the snow is deformed by the vehicles. Instrument modifications were assessed with recommendations made to further improve SMP performance for use in mobility studies.

KEY WORDS: SnowMicroPenetrometer, SMP, Microstructure, Deformation, Mobility.

1 INTRODUCTION

The U.S. Engineer Research and Development Center (ERDC) Military Engineering Program on Remote Assessment of Infrastructure for Ensured Maneuver (RAFTER) and Boreal Aspects of

Ensured Maneuver (BAEM) identifies the need for modeling over-snow vehicle performance, as many factors related to vehicle configuration and land surface conditions contribute to the economic cost of mobility. Comprehending snow macromechanical characteristics—such as elastic modulus, stiffness, and strength—is critical for understanding how effectively a vehicle will travel over snow-covered terrain. Vehicle instrumentation data (inertial measurement units and vehicle telemetry) and observations of the snowpack (both satellite and ground-based) are being leveraged to improve the modeled index for winter vehicle performance. Currently, the available mobility models are physically-based and consider numerous factors related to cross country mobility such as slope, soil type, terrain strength, land classification and vegetation. The algorithms that estimate the impact of snow cover, however, are driven by snow depth and bulk snow density alone. SMP measurements provide information on the snow microstructure and micromechanics that may improve the snowpack model.

Winter vehicle mobility studies by the CRREL have evaluated vehicle configuration and snow condition (Shoop et al. 2014); however, the SMP has not previously been applied to a mobility study. This work is the first winter vehicle mobility study to examine the performance of the SMP.

2 FIELD CAMPAIGN AND DATA ACQUISITION

2.1 Site Background

During late January 2018 at the West Yellowstone, Montana, Airport, Marine Corps vehicles were operated by the Nevada Automotive Test Center (NATC) in several snow conditions (groomed snow road, ice lane, trafficked snow, and virgin snow). The airport is closed to aircraft during the winter, and leased to NATC for their test programs. Vehicles in various performance setups (tire pressure configurations, differential configurations, towed/pulling/load carrying) conducted several types of performance tests (traction, draw bar pull, coast down). The CRREL and Boise State University snow characterization team was tasked with measuring the snowpack using a suite of instruments to record the snow conditions before and after alteration by the military vehicles. Discussed within this paper are the results from data acquired using the SMP and Rammsonde (sections 2.2 and 2.3). Figure 1 is an aerial map of the site during the summer when the ground is not snow covered.

The testing locations are identified in Figure 1 for each day of the NATC campaign. Throughout the data analysis, this report uses the following nomenclature: date (XX), cardinal location (N [north], S [south], and C [center]), snow type/location (RWY [runway], TXY [taxiway], MOBLP [mobility loop], and VS [virgin snow]), and vehicle name (e.g., MTVR [Medium Tactical Vehicle Replacement], LVSR [Logistical Vehicle System Replacement]), and test type (CD [coast down]) when applicable or unique.

Figure1. Satellite imagery of the NATC facility at the West Yellowstone Airport during snow-off conditions. Waypoints plotted indicate the test locations of the campaign.

2.2 SnowMicroPenetrometer

The SMP is a mechanically driven sonde penetrometer capable of measuring the hardness of the snowpack as a multimodal penetration force. This instrument samples the penetration force 250 times per millimeter and drives through the snowpack with a strain rate above 10^{-3} such that the snow behaves as a linear elastic material with brittle failure (Schneebeli and Johnson 1998; Shapiro et al. 1997). Thus, in theory, the SMP is capable of measuring the individual ruptures of snow crystals that are in contact with the penetrometer tip. The SMP was designed to operate in light alpine snowpacks and to be sensitive to structural weaknesses within the snowpack for understanding and assessing avalanche hazard (Schneebeli and Johnson 1998). The standard SMP load cell is sensitive to a range of forces between 0 and 42 Newtons (N) (Pielmeier and Schneebeli 2003). For the NATC West Yellowstone campaign, the SMP was equipped with a higher capacity load cell that enables measureable penetration forces up to 500 N. The hard-packed snow conditions created by and for the vehicle testing demand the increased dynamic range of the load cell. Increasing the range of the load cell comes at a cost in force resolution as the instrument's discrete quantization levels were not increased.

The SMP can acquire sub-millimeter scale force resistance profiles rapidly and with little-to-no strenuous effort by the operator in the field. Pictured in Figure 2 (left), the SMP was mounted in a sled with two runners and an open floor. The SMP sled is indexed with five positions separated by 20 cm to penetrate the snow repeatedly across a transect. After the five positions were acquired, the sled was advanced to extend the transect or to a new test location. The SMP modified with the 500 N load cell has a max penetration depth of 61 cm. When the selected depth is reached or if the SMP is unable to penetrate hard snow or the ground, the probe automatically retracts. SMP profiles are individually stored in binary .pnt files on a removable SD (Secure Digital) card. Data were acquired in a series of transects crossing perpendicular to the vehicle tracks. The typical transect would begin in the virgin snow, advance across into the tire rut, the belly drag, the second tire rut, and conclude in the virgin snow on the opposite side of the vehicle path. The resulting transect includes five SMP test locations, each with five SMP measurements 20 cm apart.

2.3 Rammsonde Penetrometer

The Rammsonde (Ram), one of the early hardness penetrometers (Bader 1954), and is the standard instrument for determining snow hardness in the field (Abele 1963). The Ram (Figure 2 (right)) has the capability of retrieving a hardness measurement within stratigraphic intervals of the snow. "Ram hardness indicates the resistance (kilograms) offered by a snow layer to the vertical penetration caused by ramming a metal cone of given dimensions" (Abele 1963). Snow microstructural properties cannot be estimated from bulk measurements of Ram hardness. The Rammsonde team sampled each test location carefully as to not disturb the snow for its measurement or the measurements of the other instruments in the field. Ram hardness profiles were recorded in the virgin snow, belly drags, and tire ruts for comparison with the SMP profiles.

Abele (1963) develops the correlation between unconfined compressive strength of processed snow and Ram hardness and conveys the underlying theory and mechanics of the tool. Abele (1963) provides an overview of the instrument design and equation (1) for calculating the ram hardness index (R):

$$R = \frac{WHn}{Z_n} + W + Q \qquad [1]$$

where W is the hammer weight, H is the drop height, Q is the weight of the penetrometer, Z_n is the penetration depth per the number of hammer blows, and n is the number of hammer blows applied to achieve a penetration interval.

Figure 2. (Left) The SMP mounted on a sled at the West Yellowstone Airport during the NATC campaign. (Right) CRREL's Dr. Sally Shoop using the Rammsonde to measure the hardness of a vehicle belly drag after a coast down test at NATC.

3 DATA ANALYSIS

3.1 Signal Processing

Hundreds of SMP penetration force profiles were acquired during the NATC campaign. Each raw SMP trace was reviewed for quality control. The quality control classifications are supplemental metadata that enables automation for the signal processing. The classification strategy in Lutz (2009) and Pielmeier and Marshall (2009) was used to identify traces that have no error (C1), exhibit a linear trend and/or an offset in the trace (C2), exhibit dampened signal micro-variance (segments of the trace that have lower variance than the normal air signal) (C3), and signals that exhibit errors of types C2 and C3 (C4). Trends and offsets are corrected if the C2 error is observable in the air signal. After repeated use, especially in wet conditions, moisture may migrate behind the penetrometer tip and introduce linear drift within the SMP signal (Lutz 2009). Data that experiences C3 errors are prevalent in this study because of the reduction in resolution of the 500 N load cell. Snow element ruptures cannot be detected in data segments suffering from C3 errors.

The binary data files are read and processed repeatedly in batch mode. The snow surface is automatically picked by the signal processing algorithm. An air gap exists between the SMP and the snow surface. In virgin snow this distance is approximately 10 cm. When the SMP is suspended above a tire rut, this distance is greater. The recorded penetration depth is therefore corrected, with zero assigned at the snow surface for each test. The processing routine corrects for instrument drift (C2 error) by a linear least squares fit applied to the data above the snow surface to estimate the drift function. The data are corrected for drift by subtracting the drift function from the raw SMP trace.

3.2 SMP Data Inversion for Snow Microstructural and Micromechanical Properties

The microstructure of snow controls its compressive strength (Marshall 2005), and is thereby important for understanding the mobility of vehicles through snow covered terrain. A physics-based theory on snow penetration through lower-density snow was first developed by Johnson and Schneebeli (1999). The snow penetration theory models microstructural snow elements as a cellular solid ice matrix that are assumed to have a constant dimension (L) that is related to the number of measured ruptures per mm (Marshall and Johnson 2009). The snow element ruptures at a rupture force (f) after some deflection length (δ) that is less than L. Snow deforming as a linear elastic material due to penetration may be defined by these basic microstructural parameters (L, f, δ) from the recorded failure of individual snow elements (Johnson and Schneebeli 1999; Marshall and Johnson 2009).

This assumption is valid in low-density snow behaving as a foam where the compaction of snow elements is understood to be negligible. In the higher density regime (400–600 kg/m^3), snow behaves as a porous solid and interelement compaction has an effect on the rupture of snow elements (Marshall and Johnson 2009). Snow densities for vehicle-driven snow and groomed snow roads are reported in the porous solid regime (Shoop et al. 2016), yet we have applied the penetration theory developed for low density snow.

Johnson and Schneebeli (1999) initially developed a Monte Carlo inversion strategy that synthesized SMP penetration force profiles by the summation of randomly distributed elements with testable values for L, f, and δ. Their results agreed well with measurements made in zirconia foam (snow analog: deformation of fresh snow by a vehicle has been successfully modeled using a crushable foam constitutive model by Shoop, et al. 2006), and indicated that the underlying theory is correct in low density snow. Marshall and Johnson (2009) made significant improvements to the original inversion strategy by accounting for errors in the recovery of the microstructural parameters, especially when L is small ($L < 1$ mm). Marshall and Johnson's (2009) data inversion was used to solve for the snow microstructural parameters. Figure 3 depicts the basic strategy of the Monte Carlo inversion. Individual snow elements with testable parameters L, f, and δ, are randomly distributed. The summed contribution of the individual elements reproduces the raw penetration force profile of the SMP when the parameters are accurately chosen, provided that the linear elastic penetration theory is sound.

3.2.1 Microstructural Parameters

The microstructural parameters (L, f, and δ) are the building blocks for 16 additional measures of snow microstructure (3.2.2) and micromechanics (3.2.3). L, f, and δ are estimated via the Monte Carlo data inversion.

- $L = \sqrt[3]{\frac{V_T}{N}}$: The structural element length. Where $A = \pi r^2$ is the area of the penetrometer tip base and z is the depth of penetration, the total volume of snow deformed ($V_T = Az$) causes N estimated ruptures.
- $f = \frac{\sum_{i=1}^{N} f_i}{N}$: The rupture force
- $\delta = \frac{F_m}{Af} L^3$: The deflection at rupture

3.2.2 Derived Snow Microstructural Parameters

The characterization of the snow microstructure quantitatively increases with the addition of microstructural parameters that are derived from penetration force (F), the basic microstructural parameters (L, f, and δ), instrument specifications (cone diameter), and inversion parameters: window length, calculation interval, and rupture threshold.

- $P_{c1} = \frac{\delta}{L}$: The probability of contact of any microstructural element, derivation 1
- $P_{c2} = \frac{N_e}{N_a}$: The probability of contact of any microstructural element, derivation 2
- N_e : The number of engaged microstructural elements
- $N_a = \frac{A}{L^2}$: The number of available elements
- $F_m = \frac{F}{2} N_e$: The mean penetration force normal to the penetrometer tip
- $F_{med} = median(F)$: The median penetration force normal to the penetrometer tip
- $\rho = 55.6(\ln(F_{med})) + 317.4$: Density model (Pielmeier, 2003)

- $T_I = 1.45 + \frac{5.72\,\sigma_F}{F_m}$: Textual index model (Schneebeli, Pielmeier, & Johnson, 1999)
- $N_T = \frac{Az}{L^3}$: The true total measured number of ruptures
- $N_m = \frac{N_T}{dz}$: The mean number of measured ruptures for a given depth window *dz*

3.2.3 Derived Micromechanical Parameters

Additionally, the three fundamental microstructural parameters (L, *f*, and δ) may be arranged into three additional mechanical properties of the snow that are useful for engineering purposes (Johnson and Schneebeli 1999).

- $k = \frac{f}{\delta}$: The coefficient of elasticity or stiffness
- $E = \frac{k}{L}$: The microscale elastic modulus
- $S = \frac{f}{L^2}$: The microscale strength

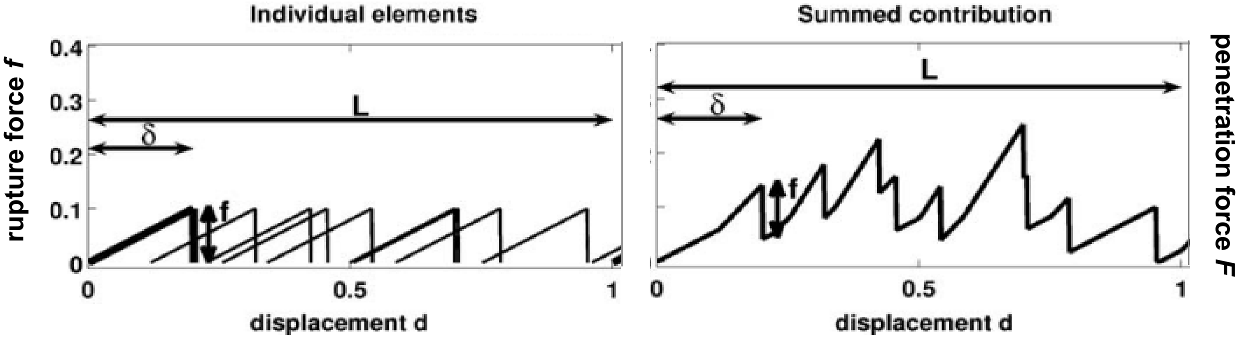

Figure 3. Adapted from Marshall and Johnson (2009). The three microstructural parameters L, f, and δ are estimated via the Monte Carlo data inversion by summing the individual modeled elements to estimate the measured penetration force.

3.3 Instrument Correlation Analysis

The above 16 microphysical parameters of the SMP data inversion, and the raw penetration force, enabled 17 independent variables to investigate correlation with the Ram hardness measurements. The median hardness value of the Rammsonde resistance was correlated with the equivalent penetration depths for a median value of each SMP microphysical parameter following equation (1).

$$r_{ij} = \frac{s_{ij}^2}{s_j s_i} \qquad [1]$$

Where r_{ij} is the linear-correlation coefficient between any two variables x_i, x_j. s_{ij}^2 is the covariance between observations of variables x_i, x_j. s_i is the standard deviation of observations of variable x_i.; and s_j is the standard deviation of observations of variable x_j.

Values of r range from 0 to ± 1 with 0 indicating no correlation and 1 indicating perfect correlation. However, the correlation coefficient solely does not indicate the goodness of correlation. r is compared to the probability distribution for the parent population that is completely uncorrelated (Bevington and Robinson, 2003). Equation (2) is the probability that a random sample of N many data points drawn from the uncorrelated parent distribution would yield an experimental linear-correlation coefficient greater than or equal to the observed magnitude of r (Bevington and Robinson, 2003).

$$P_c(r;N) = 2\int_{|r|}^{1} p_x(r;\nu)\,dx \qquad [2]$$

$$p_x(r;\ \nu) = \frac{1}{\sqrt{\pi}}\frac{\Gamma[(\nu+1)/2]}{\Gamma(\nu/2)}\ (1-r^2)^{(\nu-2)/2} \qquad [3]$$

For this analysis, a range of snow conditions in the measured data is important. Sample sizes used in the correlation analysis depend on the number of locations where the experiment was conducted and the number of snow conditions available for operation of the instrument or experiment. The Rammsonde could perform in all snow conditions encountered at NATC and was tested at nearly all test locations (N = 24). We use the correlation value and probability of significance to jointly evaluate and narrow the results to the few parameters that show promise for extrapolating to macroscale snow physics.

4 RESULTS

We developed an automated signal processing routine for the SMP signal by joining the preprocessing and classification strategy of Lutz (2009) with the inversion methods of Marshall and Johnson (2009). Rammsonde and SMP profiles were gathered from the colocated test points and were classified into three snow conditions: virgin snow, vehicle belly drag, and tire ruts. Correlation analysis was conducted using the median values from Of the 17 possible correlations, four are statistically significant: rupture force (f), mean penetration force (F_m), density (ρ), and strength (S) ($p \leq 0.05$). Figure 4 summarizes data that provide significant correlations. The data also express the trends that rupture force, penetration force, density, strength, and Ram hardness all increase when the snow was deformed by the vehicles.

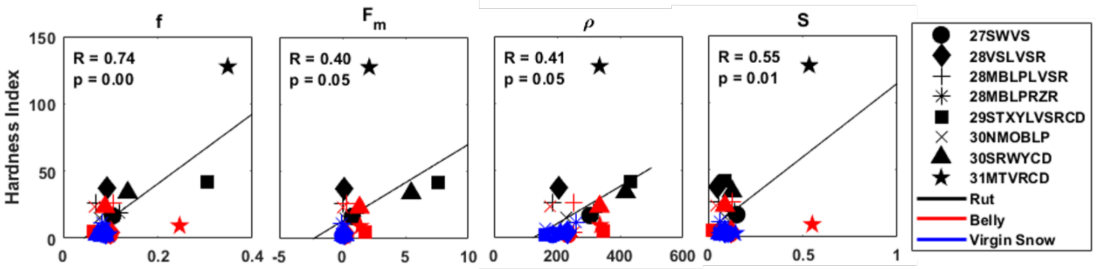

Figure 4. Statistically significant correlations between SMP microphysical parameters and the Rammsonde. The marker style identifies the site location and snow type.

Measured ruptures are sensitive to the force discretization during signal analogue to digital conversion (ADC) and during the inversion process. We find it is more robust to study rupture force than penetration force because the magnitude of the rupture is absolute, so this parameter does not suffer from errors caused by instrument drifting. Type C3 errors cannot be remedied by signal processing, and must be accepted as a limitation of the hardware. Other methods of analysis were trialed. This includes using the maximum value and normalizing each test location by the median prior to correlation analysis. However, the median value correlation provided the strongest results. Abele (1963) correlated Ram hardness with unconfined compressive strength. Because Ram hardness measured at NATC was typically too low, Abele's (1963) correlation of Ram with compressive strength does not yield physically meaningful results for this study. The significant correlation between Ram hardness and SMP strength coincides with Abele's (1963) findings, though the strength estimated by the SMP is a multimodal rather than unconfined compressive strength. This serves as a check on the methods being developed in a lower range of snow strengths and densities (approximately 100–450 kg/m^3).

5 CONCLUSIONS

The 2018 winter testing at NATC allowed the SMP to be compared with more traditional snow characterization instruments, specifically the Rammsonde Penetrometer. After signal processing protocols were established, to the SMP data parameterized the snow microstructure and micromechanics by a moving window statistical inversion. The SMP has not previously been applied to vehicle tracked snow. Groomed snow roads and snow after deformation by vehicles exhibit high density and strengths that exceed the capability of the current SMP design. By increasing the SMP load cell to 500 N, we have shown that of the 17 possible correlations, four are statistically significant: rupture force (f), mean penetration force (F_m), density (ρ), and strength (S) ($p \leq 0.05$).

To further improve the capability of the SMP for vehicle studies, a more powerful tool that can drive through hard snow at a constant rate and uses a larger bit ADC should be developed to better resolve penetration forces in hard snow. The new equipment should be designed to minimize type C2 and C3 errors. Advancements to the instrumentation should also be met with advancements to the penetration theory. By accounting for snow ruptures influenced by interlocking snow elements away from the penetrometer tip the theory of penetration in hardened snow can be improved.

ACKNOWLEDGEMENTS

Funding for this project was provided by the Assistant Secretary of the Army for Acquisition, Logistics, and Technology under project number 465395, “Boreal Aspects of Ensured Maneuver (BAEM),” which is part of the U.S. Army Engineer Research and Development Center (ERDC) 6.2 Remote Assessment of Infrastructure for Ensured Maneuver (RAFTER) Program managed by Ms. Danielle Whitlow. This work is continuing under project number 471941 "Remote Assessment of Snow Mechanical Properties" under the Entry and Sustainment in Complex Contested Environments Program managed by Dr. John Rushing. Many others helped with the testing for this work including Charles Smith, Mike Ekegren, and Wendy Wieder of ERDC-CRREL. ERDC-CRREL and Boise State University gratefully acknowledge the cooperation of the staff at NATC.

REFERENCES

Abele, G. (1963). A correlation of unconfined compressive strength and ram hardness of processed snow. *Technical Report*85. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

Bader, H. (1954). *Snow and its metamorphism*. Wilmette, Ill.: Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U.S. Army.

Bevington, P. R. and Robinson, D. K. (2003) *Data Reduction and Error Analysis for the Physical Sciences*. 3rd edn. McGraw Hill. https://cds.cern.ch/record/1305448.

Johnson, J. B., and Schneebeli, M. (1999). Characterizing the microstructural and micromechanical properties of snow. *Cold Regions Science and Technology*, *30*(1–3), 91–100. https://doi.org/10.1016/S0165-232X(99)00013-0

Lutz, E. R. (2009). Spatial and temporal analysis of snowpack strength and stability and environmental determinants on an inclined, forest opening. *Ph.D. Thesis*. Montana State University.

Marshall, H. P. (2005). Snowpack spatial variability: Towards understanding its effect on remote sensing measurements and snow slope stability. *Ph.D. Thesis*. https://doi.org/10.1093/nar/gkr409

Marshall, H. P., and Johnson, J. B. (2009). Accurate inversion of high-resolution snow penetrometer signals for microstructural and micromechanical properties. *Journal of Geophysical Research*, *114*(F4), F04016. https://doi.org/10.1029/2009JF001269

Pielmeier, C. (2003). Textural and mechanical variability of mountain snowpacks. *Ph.D. Thesis*. Universität Bern. https://doi.org/10.1023/B:GEOP.0000006073.25155.b0

Pielmeier, C., and Marshall, H. P. (2009). Rutschblock-scale snowpack stability derived from multiple quality-controlled SnowMicroPen measurements. *Cold Regions Science and Technology*, *59*(2–3), 178–184. https://doi.org/10.1016/j.coldregions.2009.06.005

Pielmeier, C., and Schneebeli, M. (2003). Stratigraphy and changes in hardness of snow measured by hand, ramsonde and snow micro penetrometer: a comparison with planar sections. *Cold Regions Science and Technology*, *37*(3), 393–405. https://doi.org/10.1016/S0165-232X(03)00079-X

Schneebeli, M., and Johnson, J. B. (1998). A constant-speed penetrometer for high-resolution snow stratigraphy. *Annals of Glaciology*, *26*, 107–111. https://doi.org/10.1017/S0260305500014658

Schneebeli, M., Pielmeier, C., and Johnson, J. B. (1999). Measuring snow microstructure and hardness using a high resolution penetrometer. *Cold Regions Science and Technology*, *30*(1–3), 101–114. https://doi.org/10.1016/S0165-232X(99)00030-0

Shapiro, L. H., Johnson, J. B., Sturm, M., and Blaisdell, G. L. (1997). Snow Mechanics Review of the State of Knowledge and Applications. ERDC/CRREL TR-97-3. Hanover, NH:

Shoop, S., K. Kestler, and R. Haehnel. 2006. Finite element modeling of tires on snow. Tire Science and Technology, 34(1): 2–37.

Shoop, S. A., Knuth, M. A., and Wieder, W. L. (2014). Vehicle Impact Testing of Snow Roads at McMurdo Station, Antarctica. ERDC/CRREL TR-14-9. Hanover, NH:

Shoop, S. A., Uberuaga, J., Wieder, W. L., and Melendy, T. D. (2016). Snow-Road Construction and Maintenance. ERDC/CRREL TR-16-16. Hanover, NH:

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE (DD-MM-YYYY) August 2020

2. REPORT TYPE Final

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE

SnowMicroPenetrometer Applications for Winter Vehicle Mobility

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER 465395

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

T. Meehan, H. P. Marshall, E. Deeb, and S. Shoop

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Cold Regions Research Laboratory
U.S. Army Engineer Research and Development Center
72 Lyme Road
Hanover, NH 03755

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CRREL MP-20-4

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Assistant Secretary of the Army (AL&T)
103 Pentagon
Washington, DC 20314

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Originally published in *Proceedings of the 18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference*, 18–22 August 2019, Quebec City, Quebec, Canada.

14. ABSTRACT

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) provides cold regions research and development in support of the US military and the nation. For winter military operations this support includes vehicle mobility modeling over snow. Many factors relate to vehicle performance, fuel efficiency and operation efficiency, including the vehicle specifications and the land surface conditions. Comprehending snow macromechanical characteristics – such as elastic modulus, stiffness, and strength – is critical in understanding how effectively a vehicle will travel over snow covered terrain. Vehicle instrumentation data (inertial measurement units and vehicle telemetry) and observations of the snow pack (both satellite and ground-based) are leveraged to improve the modeled index for winter vehicle performance. Currently, the available mobility models are physically-based and consider numerous factors related to cross country mobility such as slope, soil type, terrain strength, land classification and vegetation. The algorithms related to the impact of snow, however, are driven by snow depth and bulk snow density alone. This research deployed a SnowMicroPenetrometer (SMP) whose capabilities were expanded to measure several types of snow, including virgin snow, vehicle tracked snow and processed or groomed snow roads. The SMP high-resolution snow structural profiles show the value of the instrument as a tool for mobility studies. Correlation analysis was conducted between the SMP and Rammsonde penetrometer using median values from different snow types at a particular site. The data express a trend that rupture force, penetration force, density, strength, and ram hardness increases when the snow is deformed by the vehicles. Instrument modifications were assessed with recommendations made to further improve SMP performance for use in mobility studies.

15. SUBJECT TERMS

SnowMicroPenetrometer, SMP, Microstructure, Deformation, Mobility

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	SAR	13	**19b. TELEPHONE NUMBER (include area code)**

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18